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Abstracts of
the 37th Nordic Geological Winter Meeting
13th–15th January 2026, Turku, Finland



UNIVERSITY
OF TURKU



Åbo Akademi
University



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HELSINGFORS UNIVERSITET
UNIVERSITY OF HELSINKI

Edited by:
Jussi S. Heinonen
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The 37th Nordic Geological Winter Meeting

13th–15th January 2026, Turku, Finland



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Foreword

The Geological Society of Finland had a great pleasure to host the 37th Nordic Geological Winter Meeting in Turku, Finland. The meeting brought together researchers from the Nordic countries and beyond, representing all disciplines within geosciences. Since its inception in 1954, the Nordic Geological Winter Meeting has become a well-established biennial tradition within the Nordic geoscience community.

The meeting's characteristically Nordic "modest" size has a distinct advantage, offering a productive and inclusive working environment where researchers can easily interact, share ideas, and build networks. The theme of this year's meeting, "World in Transition", highlighted the interdisciplinary and forward-looking nature of modern geoscience research. This abstract volume contains 472 abstracts from 35 sessions and three honoured plenary presentations (one of them by the recipient of the Nordic Geoscientist Award) delivered over the three days of the meeting. Overall, the meeting attracted a total of 565 participants.

Organising a meeting of this scale required nearly two years of planning, and we gratefully acknowledge the many individuals and organisations who contributed to its success. In particular, we honor the Scientific Committee and session conveners for their essential roles in attracting a large number of high-quality abstracts. In addition, the conference included two premeeting short courses and several committee assemblies during the meeting. Last but not the least, this conference would not have been possible without the generous support of our sponsors and exhibitors, the City of Turku, and the Federation of Finnish Learned Societies.

We hope that the 37th Nordic Geological Winter Meeting has strengthened discussion and communication among scientists across disciplines, with its positive impact becoming evident in the years ahead.

On behalf of the organizing committee,

Prof. Esa Heilimo

University of Turku

Geological Society of Finland

Program

Pre-conference workshops:

11th–12th January 2026: **Metamorphic petrochronology workshop**

Organisers and presenters: Kathryn Cutts (GTK), Mahyra Tedeschi (GTK), Jonathan Pownall (Uni Helsinki), Nolwenn Coint (NGU), Naomi Tucker (GTK), Chris Clark (Curtin) and Ben Knight (Curtin)

12th January 2026: **Short Course on Orogenic Gold Systems**

Organisers and presenters: Jochen Kolb (Karlsruhe Institute of Technology), Iain Pitcairn (Stockholm University), Nicolas Thebaud (University of Western Australia), Pasi Eilu (University of Turku)

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07:30	Logomo entrance hall 07:30-08:30 Registration					
08:30	Logomo hall 08:30-09:00 Opening ceremony					
09:00	L... 09:00... 34. Scientific computing and artificial intelligence in Earth science 4	Te: 09:00... 37. Structural geology and resources 3	Ki 09:00... 19. Hydrogeology 4	LC 09:00... 2. Applied geochemistry 4	G... 09:00... 18. Hominin palaeoenvironments and the Anthropocene 4	G... 09:00... 11. Geophysical signatures of mineral systems and across scales 4
10:00	Logomo entrance hall 10:00-10:30 Coffee					
10:30	Lo... 10:30... 21. Magmatism from the Archean to the present: insights and analogues 4	Te: 10:30... 37. Structural geology and resources 5	Ki 10:30... 19. Hydrogeology 6	LC 10:30... 2. Applied geochemistry 6	G... 10:30... 18. Hominin palaeoenvironments and the Anthropocene 5	G... 10:30... 11. Geophysical signatures of mineral systems and across scales 6
12:00	Logomo entrance hall 12:00-13:00 Lunch & posters 143 submissions					
13:00	Logomo hall 13:00-14:00 Plenary, P. David Polly: Clasts with minds of their own: new approaches to interactions between organisms and Earth systems 1 submission					
14:00	Lo... 14:00... 21. Magmatism from the Archean to the present: insights and analogues 4	Te: 14:00... 37. Structural geology and resources 3	Ki 14:00... 38. Subglacial to ice-marginal processes, landforms and sediments 4	LC 14:00... 2. Applied geochemistry 2	G... 14:00... 28. Planetary science: Open session 4	G... 14:00... 33. Satellite and airborne remote sensing and geophysics solving present geological and geoenvironmental challenges 3
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15:00	Logomo entrance hall 15:00-15:30 Coffee					
15:30	Lo... 15:30... 21. Magmatism from the Archean to the present: insights and analogues 5	Te: 15:30... 10. Geomodelling across time and space 5	Ki 15:30... 38. Subglacial to ice-marginal processes, landforms and sediments 4	LC 15:30... 22. Mineralogy as an enabler of transition 5	G... 15:30... 1. Advancing circularity in the extractive industries 6	G... 15:30... 33. Satellite and airborne remote sensing and geophysics solving present geological and geoenvironmental challenges 6
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14th January 2026:

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15th January 2026:

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PLENARY 1

Clasts with minds of their own: new approaches to interactions between organisms and Earth systems

P. David Polly

Indiana University, Bloomington, Indiana, USA

Understanding the processes past and present that shape the Earth and its environments is a goal of geosciences. Advances have been achieved by linking Earth materials to processes through their physical and chemical properties like Hjulstöm's diagram that linked processes of erosion, transport, and deposition to particle size and fluid flow or Emiliani's demonstration that paleotemperature curves could be reconstructed from oxygen isotopes because of the relationship between temperature and evaporative probability. The fossil record documents the interaction of life and Earth systems, but to anyone but a paleontologist its arcane tangle of taxonomy, morphology, and biostratigraphy can be a barrier to understanding large-scale processes. The difficulty is that organisms evolve in response to their environments. While sand-sized sedimentary particles have the same relationship to fluid flow in the Proterozoic as they do today, the relationship of species to any Earth system differs by both time and place. In this talk I review new trait-based approaches to the fossil record know as "ecometrics". Instead of focusing on the rise and fall of species, ecometrics focuses on the functional relationship between measurable traits and their corresponding systems. Examples include the shapes of leaves and rainfall, the durability of teeth and aridity, and the size of ectothermic animals and temperature. By focusing on functional relationships, it becomes possible to study the responses of life to changing environments and to understand causal relationships between deep-time events and the evolution of life. The development of the ecometric approach owes a great deal to Nordic scientists.

PLENARY 2

Geoscience as the Engine: Collaboration, Innovation, and Discovery in a World of Transition

Julie Hollis

EuroGeoSurveys

Energy systems are shifting at unprecedented speed, climate impacts are accelerating, and geopolitics are reshaping supply chains and resource landscapes. In this context of these rapid and intersecting developments, geoscience provides the capacity to understand the Earth as an integrated system, to interpret past change, and to anticipate future conditions. As society transitions across multiple domains simultaneously—low-carbon energy, critical raw materials, groundwater security, urban resilience, carbon storage—geoscience can deliver key input to much-needed solutions. But responding effectively requires not only scientific excellence: it requires human-centred communication, inclusive scientific culture, and commitment to collaboration. This is because innovation is not just a technical process—it is a social one. Innovation thrives where people feel engaged, included, and valued. Across the geosciences we see powerful evidence that collaboration and communication determine not only the pace of scientific discovery but also its impact. This keynote explores how geoscience can lead in a world of transition by strengthening the connections between discovery, innovation, and community. It argues that the future of geoscience—and the resilience of society—will depend on our willingness to collaborate openly, to think boldly, and to recognise that our greatest scientific instrument is, ultimately, each other.

PLENARY 3 (Recipient of the Nordic Geoscientist Award)

Ice Ages, Gas Hydrates and Massive Methane Venting in the Arctic

Karin Andreassen

iC3 – Centre for ice, Cryosphere, Carbon and Climate Department of Geosciences UiT, The Arctic University of Norway, Norway

This invited Award Lecture focuses on the impacts of grounded ice sheets on methane emissions in the Polar North Atlantic Ocean. Methane (CH₄) is a strong greenhouse gas, second most important after CO₂. It has approximately 84x higher warming strength compared to CO₂ over a 25-year timescale and may be a key driver of global warming in the short term. Understanding and quantifying of methane emissions have attained significant attention in recent decades. Here I present evidence for extensive and widespread leakage of gas and oil from deeper hydrocarbon reservoirs into the Barents Sea. Hot spots of gas flares in the water and oil slicks on the sea surface correlate to underlying, former glaciated structural highs which have experienced km-scale of glacial erosion. This has left hydrocarbon reservoirs partially uncapped and heavily faulted.

Combined with numerical modelling of ice sheet and gas hydrate development, our results indicate that during glaciation, hydrocarbons migrated upwards from deeper reservoirs and were sequestered extensively as subglacial gas hydrates. Upon ice sheet retreat, methane often concentrated in gas hydrate mounds before being abruptly released to form craters. Deeper gas hydrates, including heavier hydrocarbon gases, are stable longer and still exist in parts of the Barents Sea. We propose that similar geologically controlled, extensive gas venting may be characteristic of formerly glaciated hydrocarbon-bearing basins which are common across polar continental shelves. This could represent an underestimated source of methane within the global carbon cycle and could also provide an analogue for future methane release from contemporary ice sheets.

O1.1

Process options evaluation using a circular economy framework

Inka Orko¹, Päivi Kinnunen²

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The current mining and minerals processing operations typically have a rock-to-metal ratio of 10^5 – 10^6 for precious metals, and for iron ore and aluminum in the order of 10^1 (Nassar et al. 2022). Thus, more than 90 percent of the material typically is disregarded in waste rock, tailings and other side streams. This practice is wasteful, and we lose the value of any potential process co-products (Kinnunen et al. 2022).

A few companies are already active and extracting valuable side metals or other components from residues and side streams; we call this the *added value strategy*. However, this is not always techno-economically feasible due to the current chemistry and processing used to extract the main component, and in addition, such operation leaves the bulk of the residue unutilized. Thus, we propose an evolutionary circular strategy: to re-design a multi-product process utilizing different technologies that allows the extraction of most components, metallic or other compounds (Kinnunen et al. 2022) to products. The products can also be unconventional and intermediate products for specific uses; we call this the *circular-by-design strategy*.

Such comprehensive process design requires balancing between the product market, technology options, environmental considerations, and techno-economy and cost. We need to identify any trade-offs, such as energy consumption vs. product yield vs. investment payback time. We also need to consider the company capabilities, value chain maturity etc. when moving out to new products.

In this paper we present a framework and a comparative preliminary assessment for the framework on two circular economy concept cases: a business-as-usual and a circular-by-design concept. The framework is based on the approaches by Saari et al. (2024) and Hakola et al. (2024).

Acknowledgments

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O1.2

Embedding Circularity in AI-Enhanced Mine Planning: Block Model Optimisation for Critical Raw Material Recovery

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The rapidly expanding demand for Critical Raw Materials (CRMs), such as graphite, lithium, cobalt, and nickel, illuminates pressing mining and resource governance challenges in a transition to a low-carbon economy. Despite ongoing research on the availability and substitutability of CRMs, global risk analysis consistently indicates these materials are vulnerable based on concentrated supply lines, exponential demand, and poor recycling potential (Arrobas et al. 2017; IEA 2025; USGS 2025). Existing technologies, though advancing, remain insufficient to bridge these supply shortages, often propelling higher expenses and greater dependence upon a few producing nations (European Commission 2024).

This work employs a wide-ranging approach based upon a review of the literature, global case histories, and discussions with industry practitioners and research academics. These studies discovered ongoing gaps between CRM demand profiles and mining system technological ability. Whereas previous work has explored optimisation frameworks for scheduled mines (Blom et al. 2024), to date, no work has combined Artificial Intelligence (AI) as a constituent of block models or in optimisation processes to identify CRM mining potential.

The most significant contribution of this research is in proposing AI-enhanced mine planning as a novel remedy for filling this gap. The method encompasses the incorporation of CRM properties in block models such that optimisation algorithms can consider variability in geology as well as a strategic vulnerability of core resources. The scope extends far beyond in-operation mine planning. It assumes greater importance as available traditional technologies are found inadequate for supply-demand, leading to a steep increase in cost and manifold increase in supply risk (World Bank 2017; Harper et al. 2019).

Technological optimisation can help policymakers, industry players, and researchers identify where sustainable mining aligns with global critical resource management (CRM) security. This research contributes to discussions on how mining systems can evolve for greater efficiency and long-term sustainability.

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O1.3

Reprocessing tailings for circular economy practices in the mining sector

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CINTEM project “Circularity-integrated mining” funded by Business Finland (grant no. 3397/31/2024) focuses on advancing circularity in both brownfield and greenfield mining operations. Tailings pose environmental risks and financial liabilities, but they can also serve as secondary metal sources, offering both economic and environmental benefits. This study examines the potential of tailings reprocessing to contribute to a circular economy in mining, assessing its economic and environmental implications for commercial operations.

Reprocessing tailings requires either high metal concentrations or subsequent use of residues to reduce environmental impact and improve economic returns. The full material stream—valuable metals, by-products, and bulk minerals—should be considered in a holistic way in reprocessing. Some tailings fractions can even be upcycled into higher-value products, offering benefits over virgin materials. Despite the significant quantities, commercial production of metals from mine waste is still very limited.

Identified commercial tailings reprocessing cases indicate increasing commercial interest in tailings valorisation, though the actual full-scale operations are rare. One of the challenges is the lack of knowledge on the contents of historical tailings. The focus is typically on one target metal that was recovered already earlier. An example of a more holistic approach focusing on several metals and minerals was also identified. Companies used internal development, mergers and acquisitions, and partnerships as strategies to enter tailings reprocessing business. The transformation provides business opportunities also to new kinds of stakeholders in the field.

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O1.4

Environmental implications of Mg-silicate resource extraction, feedstock processing, and waste management for industrial scale ex-situ carbon storage by mineralization (CSM)

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Reprocessing of mine waste is viewed as a transformative opportunity for the mining industry to advance circular economy and decarbonation goals, while simultaneously reducing environmental and social impacts of mining and mine waste disposal. Integrating ex-situ carbon capture and utilization via mineral carbonation (hereafter, CSM for carbon storage by mineralization) into mining and (re-)processing could enhance these benefits and the economic viability of ex-situ CSM by converting mine waste and CO₂ into valuable products (IEAGHG 2022, Milani et al. 2025). However, implementation of mine waste reprocessing and large-scale ex-situ CSM remain limited: notable gaps exist in understanding the environmental and social benefits and drawbacks, despite environmental risk reduction being a key driver (Maest 2023; Holley et al. 2025; Milani et al. 2025).

As a part of the Piloting ÅA CCU project developing so-called ÅA routes for ex-situ CSM towards industrial scale (>0,1 Mt CO₂/a) deployment in Finland (Zevenhoven et al. 2025), this study aimed to understand the environmental implications of the associated Mg-silicate resource extraction, feedstock processing, and waste management. To this end, a conceptual model integrating CSM into mineral extraction and processing was developed. The model distinguishes between prospective resource types (Mg-silicate rocks, tailings, waste rock) that could be processed to produce CSM feedstock. Major operations and residual streams were outlined. The residue volume, properties, reuse potential and waste disposal aspects were preliminarily assessed.

Mg-silicate resource extraction, CSM feedstock processing and Mg-leaching of the feedstock generate residues with variable characteristics and volumes, with the first two largely influenced by the resource type. Suboptimal CSM feedstock and inefficient leaching produce tailings with poor environmental properties, requiring costly and resource-intensive waste management solutions. The insight into residue generation and characteristics reveals opportunities to improve the environmental performance (e.g., tailings properties). This study underscores the value of an iterative, interdisciplinary approach that considers resource-specific residue profiles. It highlights that beyond CO₂ budget and (by-) product valorization, resource efficiency, residue characteristics and waste disposal are important for the environmental viability of such projects.

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O1.5

Engine Failures Caused by Dust from Asphalt Containing Ferrochrome Slag: A Circular Economy Byproduct from Stainless Steel Production

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Circular economy encourages industries to produce byproducts instead of waste (Mhatre et al. 2021). More research on novel materials is needed (Krajewska & Siewczyńska 2025). Our study relates to the “Oulu disease” in northern Finland that causes unusual break down of timing gears in car engines. The phenomenon has not been reported elsewhere and its cause remained unknown until our study. We ruled out factors like local climate or geology that do not differ significantly from those in adjacent Baltic Sea regions. One difference is the use of FeCr-slag, a CE-marked byproduct of stainless-steel production, to replace natural aggregate in asphalt in the Oulu region. The use of slag is due its technical properties, and the proximity of the EU's only Cr mine in Kemi and a stainless-steel factory in Tornio.

A premise of our study was that street dust in the Oulu region has an abrasive component that enters engines and damages them. Evidence of this include reshaped sharp edges and scratches on pulley teeth and iron dust in the timing gear housings. We collected dust and engine parts from car engines and carried out an asphalt mapping, while SYKE and Metropolia conducted street dust sampling. The samples were examined using SEM-MLA, XRD and μ XRF for the particle composition, shape and size, and to inspect the engine parts. Also, test dusts were prepared using common asphalt aggregate types from the region to study their abrasiveness with test engines at the University of Oulu. The results showed that slag dust is highly abrasive forming shard-like particles due to its hardness and low crystallinity degree. The abrasion rate was >25 times higher with slag dust than with dust produced from natural rocks. The abrasion is likely a 2-body abrasive wear (Jensen & Aghababaei 2023) as the slag particles adhere to the timing belt and wear out the pulleys.

As a result of our study 400 km of asphalt pavement will be renewed in northern Finland. This outlines the importance of in-depth research before introducing new circular economy materials. Few studies (e.g., Dziubak & Dziubak 2022) focus on street dust primarily from environmental safety and technical viewpoints. Health risks of FeCr-slag dust are also highlighted as is the need for more study related to its mineralogy, shape, size, surface properties, and chemical composition.

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O1.6

Circular Economy Field-testing Facility for Extractive Waste and Side Streams

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Utilization of extractive and industrial side streams in closure of extractive waste areas provides an opportunity to reduce the use of virgin materials and disposed waste. This increases the circularity and sustainability of the extractive industry. Yet, the use of side streams in closure solutions such as covers requires verified data on their geotechnical and environmental performance to ensure their suitability. Extractive waste management also requires reliable data on the long-term behaviour of wastes. Such data has traditionally been produced at laboratory scale, but recently there has been an increasing focus on developing field tests to better simulate the behaviour of wastes and closure solutions under local climatic conditions and to improve the scalability of the data to operational scale.

To facilitate reproducible, effective testing of extractive waste and side streams, a customizable and instrumented field-testing site, GTK SMARTTEST, has been set up at the GTK Mintec mineral processing pilot plant in Outokumpu, Finland. The concept includes small-scale and large-scale tests. The smaller scale 1 m³ IBC container tests are used to test a selection of closure options, such as various cover structures and the applicability of side streams in covers. The large-scale tests, 10-20 m³ in size, are constructed to mimic operational conditions of selected closure solutions and to study novel waste disposal techniques, e.g. dry stacking of tailings or co-disposal techniques of tailings and waste rocks, to decrease environmental impacts of waste disposal and support their management.

The large-scale tests are constructed of re-usable concrete blocks, and they include high-density polyethylene (HDPE) liners to ensure water collection from the tests. In both test sizes, the geochemical and geotechnical changes in the studied materials are monitored using sensors (EC, T, O₂, moisture, water potential) and by analysing the quantity and quality of pore water as well as drainage and seepage water collected through well systems in the bottom of the test structures. Moreover, lidar scanning is used to detect changes in geotechnical stability of the materials, such as settlement or erosion. Comprehensive geochemical, mineralogical and geotechnical characterization of the tested materials before and after the tests contributes to understanding of the behaviour of the materials and the performance of the tested solutions. Currently, the on-going field tests include tests studying covers and encapsulation using side streams, co-disposal of different types of waste rocks, and dry stacking of tailings.

Combining a mineral processing pilot plant with such a field-testing facility enables early testing of extractive wastes to support a design-based approach and an early planning of extractive waste management adapted to the actual waste characteristics. This also promotes the use of circular-based side streams in the management of extractive waste.

P1.1

Circularity in the European Battery Regulation A 9R framework analysis of regulatory levers across the battery value chain

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The global transition to lithium-ion batteries intensifies demand for critical minerals, placing pressure on extractive industries to secure supply. The European Union's Battery Regulation (2023/1542) aims to mitigate these pressures by building a circular battery value chain. While technical advances in recycling and material recovery are well-studied, the role of policy in enabling broader circular strategies across the value chain remains underexplored.

A mixed-method content analysis of the European Battery Regulation was conducted using the 9R framework (Refuse, Rethink, Reduce, Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover). A weighted assessment, reflecting each provision's relative circularity potential, enabled a systematic evaluation of how strategies are addressed and operationalized.

The analysis shows that 'Reduce'—lowering raw material input—is the most systematically enabled strategy in the regulation. Provisions on carbon footprint thresholds, durability requirements, and minimum shares of recycled content act across the value chain to constrain material intensity in production and design. By contrast, 'Recycle' is the most frequently referenced strategy, supported by recovery targets and efficiency standards, but it ranks lowest in weighted terms as it mainly governs end-of-life flows without reducing upstream demand. Mid-tier strategies such as remanufacturing and repurposing appear only indirectly through disclosure obligations, leaving them weakly embedded.

The findings reveal a misalignment between regulatory emphasis and circularity potential. While end-of-life recycling dominates policy discourse, the strongest leverage lies in upstream provisions that reduce material inputs. For the mining sector, this implies growing pressure to deliver low-impact, traceable materials that comply with carbon footprint and recycled content requirements. Thus, the Battery Regulation not only incentivizes recycling infrastructure but also places new demands on extractive industries to align with upstream circularity goals in the evolving European battery value chain.

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P1.2

LITHOS: Cost-effective processing and refining of lithium into lithium hydroxide from strategic European multi-mineral lithium hard-rock projects

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Lithium-ion batteries play a crucial role in decarbonizing energy and mobility. LITHOS project funded by European Union supports the European Critical Raw Materials Act by targeting lithium processing and refining, contributing directly to European domestic extraction (10%) and processing (40%) goals. LITHOS processes and refines ores from three “strategic projects” for battery-grade LiOH·H₂O: Keliber’s deposits in Finland, Savannah’s Barroso project in Portugal (both pegmatite), and Imerys’ Beauvoir mine in France (Rare-Metal Granite, RMG). The aim is to reduce the cut-off grade for spodumene ores, resulting in larger Li reserves, while allowing the commercialisation of lower-grade pegmatite and RMG deposits.

LITHOS adapts the Keliber & Metso flowsheet, which was developed for regular-grade spodumene ores, for lower-grade spodumene ores and other lithium minerals, such as lepidolite or petalite. It introduces innovations along the value chain in mineral processing, concentrate pre-treatment, and hydrometallurgical refining. LITHOS also focuses on a closed-loop water system aiming for 90% less water use and targets 50% lower CO₂ emissions compared to the current benchmark. Supported by thermodynamic modelling and digital twins, LITHOS plans to extend its responsible mining and refining approach to 24 other European Li-hard-rock deposits.

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P1.3

Recovering valuable minerals from mining wastes - Benefits and challenges

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There is an increasing effort to utilize tailings and waste rock by separating the useful industrial minerals they contain into raw materials for various construction materials and other products. In addition, tailings and waste rocks have been proven to be important sources of valuable metals and minerals, including critical raw materials. The utilization of tailings and waste rock from old mines can present surprising challenges if their mineralogical or chemical composition is not sufficiently well known.

The first challenge is to find out more detailed historical data about the mine operation, and the geology and mineralogy of the mined deposit, though old historical data may be incomplete in some cases. In addition, the mineralogy of materials may have changed due to the various chemical reactions over time. In some cases, the ultra-fine particles in the tailings make reprocessing, for example by froth flotation, very challenging.

Tailings can contain high concentrations of heavy metals, depending on which minerals were originally intended to be recovered at the mine, and which minerals have been released into the waste. Minerals containing REEs almost invariably contain isotopes of uranium and thorium that generate natural radiation. These naturally occurring radioactive substances may have been concentrated in significant amounts in the tailings along with the REE bearing minerals.

Another challenge is the chemicals, which may still be present in the old tailings. Xanthates, which are used as collector chemicals, are likely to degrade over time, but many hydrocarbon-based chemicals may persist for a long time. Chemical degradation products can be harmful to the environment and health. The tailings of old mines may contain chemicals that are now banned, or the mine tailings areas may have been used as a dumpsite for other waste.

Therefore, comprehensive mineralogical and chemical studies of tailings and other mining wastes located in old mining areas are key not only to the effective recovery of valuable minerals, but also to minimize potential environmental risks. On the other hand, the reprocessing of mining waste can also lead to an improvement in the state of the environment, if in addition to recovery of valuable minerals, harmful substances, such as minerals containing heavy metals and sulphur, are also removed from the tailings.

As part of the EU-funded REMHub project, Oulu Mining School (University of Oulu) is developing new innovative methods for the recovery of minerals containing REEs, especially from mining wastes, but also from ore rocks. After mineralogical study, the mineral processing experiments are carried out first in laboratory scale, based on which the developed mineral processes workflow will be scaled up to pilot scale flotation and leaching experiments. Regarding the mineral processing of mining wastes, the above-described mining waste-related challenges are also being investigated and reported thoroughly.

02.1

Tracing the mobility and geochemistry of Mo, V, and W in Swedish rivers and headwater streams

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Critical oxyanion-forming trace metals—vanadium (V), molybdenum (Mo), and tungsten (W)—are central to green technologies yet remain under-monitored in Nordic freshwaters. We investigated their sources, transport, and partitioning across Swedish hemiboreal and boreal landscapes, analyzing 97 hemiboreal headwater streams, one boreal headwater stream, and two unregulated boreal rivers. Spatial and seasonal variability was pronounced. V occurred at the highest concentrations in hemiboreal headwaters (avg. $\sim 78 \mu\text{g L}^{-1}$) relative to Mo ($\sim 8 \mu\text{g L}^{-1}$) and W ($\sim 0.2 \mu\text{g L}^{-1}$), exceeding boreal streams and rivers by up to $\sim 300\times$, consistent with enhanced weathering under milder hemiboreal conditions. Element partitioning differed: Mo was predominantly dissolved, W spanned dissolved and particulate fractions, and V shifted from dominantly dissolved in hemiboreal streams to $\sim$ equal distribution in boreal waters. Spring snowmelt produced the strongest dynamics, with hydrological flushing and hyporheic exchange mobilizing solutes from riparian soils and porewaters. Carrier-phase relationships indicated associations of V and W with Fe- and Al-rich phases and of Mo with organic matter, Si, and U, particularly near river mouths. Redox transitions in wetlands and hyporheic zones mediated mobility—promoting V release and W transport while retaining Mo under reducing conditions.

Collectively, hydrology, redox state, and landscape type regulate the mobility and fate of V, Mo, and W from source to sea. Headwater streams emerge as biogeochemical control points where colloidal and redox processes govern metal fluxes. The differing behaviours—Mo conservative in dissolved form, W partly colloid-bound, V redox-sensitive—underscore the need for phase-resolved sampling and for integrating colloidal, redox, and hydrological processes into monitoring and modeling. These insights are directly relevant for exploration geochemistry in glaciated terrains, advanced analytical approaches, management, sharing, and visualization of geochemical information in the Nordic region. They also inform environmental risk assessment and critical raw material exploration strategies as EU demand rises and climate-driven shifts in wetland extent, DOC export, and hydrological extremes alter element transport pathways.

Our results recommend (i) headwater-targeted, time-sensitive surveys around snowmelt; (ii) concurrent dissolved/particulate and colloidal characterization; and (iii) explicit consideration of Fe/Al carrier phases and organic complexes when interpreting anomalies for Mo, V, and W in northern glaciated landscapes.

O2.2

Biominedralized gold nanoparticles and associated endophytic bacteria in Norway spruce needles (*Picea abies*)

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Biogeochemical exploration increasingly utilizes plants to detect mineralization concealed by sediment or bedrock. Previous studies have reported trace metals such as gold (Au) and silver (Ag) in trees, yet the mechanisms governing their vascular transport and deposition remain poorly understood. Microorganisms, particularly endophytic bacteria, may influence biomineralization through metal transformation, biofilm formation, and interactions with the host plant. We hypothesized that endophytic bacterial communities contribute to the occurrence of Au-nanoparticles in *Picea abies* (Norway spruce) needles. To test this, we collected 138 needles from 23 trees growing above Au mineralization in Northern Finland. Au-nanoparticles were detected using field emission scanning electron microscopy with energy-dispersive spectroscopy (EDS-FE-SEM), and 16S rRNA amplicon sequencing characterized the endophytic bacterial communities. Au-nanoparticles were found in four trees (17.4%), consistently associated with microbial cells embedded in a biofilm-like matrix. Trees with higher Au concentrations exhibited lower bacterial richness, though overall diversity and community composition did not differ between trees with and without Au-nanoparticles. Machine learning and indicator species analyses identified taxa, including P3OB-42, *Cutibacterium*, and *Corynebacterium*, as strongly associated with the presence of Au nanoparticles. These findings suggest that endophytic bacteria may play a role in Au biomineralization within spruce needles, highlighting microbial–plant interactions as an important, previously underexplored factor in biogeochemical cycling and mineral exploration.

02.3

Geochemistry of hot springs near Ittoqqortoormiit, East Greenland

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Geothermal manifestations are not widespread in Greenland. Nonetheless, hot and warm springs exist, and are mainly found in the basaltic regions, around and within Kangertittivaq (Scoresby Sound) in East Greenland and on Qeqertarsuaq (Disko Island) off the west coast. Outside these two regions only two geothermal springs are known, both in Southern Greenland, at Iksagtivaq near Tasiilaq and at Uunartoq Island. Little research has been done on possible geothermal utilisation in Greenland; limited surface exploration and no exploration drilling. This contribution describes the results of geothermal mapping and analysis of geothermal water collected in the vicinity of Ittoqqortoormiit village, near the mouth of Kangertittivaq in August 2022.

The hottest geothermal spring in Greenland, Uunarteq, is located about 7 km south of Ittoqqortoormiit, at the deserted settlement Uunartoq (Kap Tobin). The water is about 60°C and the discharge is about 1 L/s, emanating from gneiss. About 2 km ENE of the hottest spring, on the other side of a small inlet, another hot spring, Uunarterajik, discharges about 1 L/s of water at 33°C and several smaller springs are found in the vicinity with temperatures up to 45°C and total discharge at least 0.5 L/s. On the other side of Ittoqqortoormiit village, near another abandoned settlement at Itterajivit (Kap Hope) a few warm and tepid springs give water with discharge temperature from 6 to 16°C and flowrates up to 25 L/s. Although 6°C is not considered particularly hot, it is distinctly warmer than the local groundwater temperature of about 3°C. During the 2022 expedition, seven water samples for chemical analysis were collected from the springs discussed above, as well as from cold springs and surface water in the area.

The hot water at Uunarteq and Uunarterajik is brackish, with chloride concentrations from 4000 to 5400 mg/L. Silica concentrations are from 60 and 70 mg/L. Hydrogen sulphide is present at low concentrations (<0.1 mg/L) and the measured radon activity is 13-67 Bq/L. The water from the hot springs is more depleted in deuterium ($\delta D \approx -122\text{‰}$) than local surface water ($\delta D \approx -105\text{‰}$), suggesting that it is not a simple mixture between surface water and seawater. This conclusion is also supported by modelling of water-mineral equilibria which suggests that the water at Uunarteq is in equilibrium with rock at 85-90°C. These temperatures are high enough to provide water for district heating in Ittoqqortoormiit, but due to the high salinity of the water it would be advisable to use it for heat exchangers rather than direct heating.

The water from the warm and cold springs at Ittaajimmiit is fresh but shows signs of some interaction with rock. The chloride concentrations are low (2-14 mg/L), pH is higher than 9 and silica concentration 20 mg/L or less. The water is more depleted in deuterium than water at Uunartoq ($\delta D \approx -130\text{‰}$) and radon activity is about 5 Bq/L. Geothermometry does not suggest higher reservoir temperature.

O2.4

Snow as a mineral exploration tool

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Mobile Metal Ion (MMI) theory has become important process in mineral exploration, and it has many applications nowadays. Basic idea is that metal ions and certain hydrocarbons released from the mineralisation in the bedrock migrate through the surficial part of the bedrock and transported cover to be accumulated into the surficial soil horizons. These ions and hydrocarbons will be loosely bound to the surface of mineral grains and organic material or will be stacked into different trap sites. With different weak and selective leaching techniques ions can be separated from the mineral matrix for analyzing element concentrations. The same horizons are also the main source for nutrients which plants are in-taking, and have significant influence to biogeochemical application.

One of the latest applications to MMI theory is snow geochemistry. Snow is very promising, new sample material that can be used in mineral exploration. Exogenic geochemical signal of elements and hydrocarbons formed into the snow can be used in analysis of the elemental composition and tracing the potential mineralization in the underlying bedrock. Even in winter the migration continues, and carbon dioxide and water vapor as well as various volatile hydrocarbons and ions accumulate in the bottom layers of snow cover (in the areas where snow cover exists), where they adhere and bind into snow crystals.

The lower part of the snow cover serves as the best ion binding layer, as the formation time of geochemical signal is the longest, and the upper layers of snow protect against atmospheric contamination during the winter. In addition, the lowest layer is in contact with the ground and is affected by gases and heat from the underlying soil and bedrock. In the northern regions, snow covers the ground surface for several months in a year, although recent results show that even one month is enough to form strong geochemical signal. It means that the method is usable on moderately large areas in the Northern Hemisphere and mountainous areas. Snowfall and snow properties are regionally constant, which provides a good basis for extensive and comparable geochemical exploration. Snow cover provides easy access to all kinds of terrains during wintertime and snow sampling can be done without leaving traces to the ground and environment.

There are several examples in Finland how the snow geochemistry has been used as an effective exploration tool for different types of mineralization. The strongest contrast is found in the mineralizations where sulfide minerals are present, such as in orogenic gold deposits and hydrothermally altered, vein-type and/or VMS-type deposit Cu-Co-Ni occurrences. However, good anomaly patterns have also been found in the case of IOCG and phosphate deposits. Experiments prove that snow geochemistry is not only working for tracing surficial or suboutcropping mineralizations but also for deep-seated ore deposits.

Acknowledgments

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02.5

Lithium potential of till estimated with portable devices (pLIBS and pXRF)

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In this study, portable devices' (LIBS and XRF) suitability for till analysis is evaluated in study area where lithium-bearing pegmatitic boulders and an outcrop have been discovered.

Typically, till samples are collected in field, transported to a laboratory and dissolved into acids (e.g. 4-acids, aqua regia) and analysed with ICP-MS or ICP-OES. Lithium ore mineral spodumene (LiAlSi₂O₆) is a silicate mineral which dissolves poorly to traditionally used aqua regia. Spodumene also tends to be more in coarser fraction of till than the silt and clay fraction commonly used in exploration (e.g., Brushett et al. 2024). However, the aim here is to present how lithium potential of the area can be detected from the adjacent till only by analysing small sized samples with a fast on-site measurement protocol.

Using LIBS (laser-induced breakdown spectroscopy) in lithium detection is widely acknowledged, and the benefits of this method in lithium-bearing spodumene pegmatite analysis have been demonstrated earlier (Romppanen et al. 2023). Meanwhile, portable XRF offers a way to quickly analyse heavy elements in the samples without strong matrix effect that causes challenges for quantitative LIBS analysis. A combination of these methods offers a way to reach full geochemical information of analysed till samples. Challenges conducted by a small sample size and the matrix effect of LIBS can be overcome with the right sampling design and robust data analysis. The presented analytical protocol forms a base on how small-sized till samples can offer information about the area's lithium potential without time-consuming heavy sample preparation and laboratory-based analytical procedures.

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O2.6

Geochemical soil baselines of mineral potential areas and mining surroundings in Finland

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Since 2016, the Geological Survey of Finland (GTK) has examined soil geochemical baselines in mineral potential areas and mining surroundings. The samples represent both topsoil and subsoil, and the parent material of studied samples is mainly glacial till, which is the most common superficial deposit type in Finland.

To date, a total of 21 mineral potential areas and mining surroundings, with a total of 1408 soil samples, have been examined. In these studies, sites influenced by anthropogenic activities were avoided. In addition to soil samples, some humus as well as groundwater and surface water samples, have been investigated from these sites. The near-total element concentrations in soil samples were determined from <2 mm grain size fractions using *aqua regia* leaching. The upper limits of regional soil baseline variation (hereinafter geochemical baseline) for arsenic and potential harmful metals (hereinafter PHEs) were calculated for each study area.

In many investigated areas, the geogenic concentrations of PHEs in soil parent material exceeded the Finnish threshold values prescribed in a Government Decree on the Assessment of Soil Contamination and Remediation Needs (214/2007). In the eight study areas around the metallic mineral deposits or mines (Au), the threshold value of at least one PHE was exceeded. In research material from ten sulphide mineral deposits or mining surroundings in seven areas, at least one PHE in soil parent material exceeded the Finnish threshold values. In the soil parent material of the two studied oxide ore mining surroundings, three and four PHEs exceeded the threshold values, respectively. In the mineral potential area of phosphate, iron and REE surroundings, five PHEs exceeded the threshold values in the soil parent material.

In seven of the 21 studied mineral potential or mining surroundings areas, the calculated geochemical baselines in soil parent material were below the Finnish threshold values. In eight cases, the geochemical baseline was exceeded by arsenic or nickel, in five cases, by cobalt, in four cases, by chromium; and in one case, by vanadium.

Geochemical baseline data plays a key role in land use planning, especially when evaluating potential soil pollution, the need for remediation, and the suitability of excavated soil for reuse. Based on the Decree (214/2007), the regional or local upper limit of geochemical baseline for PHEs can be used instead of soil threshold value. In addition, geochemical baselines are important background information for risk assessment procedures. It is essential to provide end-users with nationally comparable and scientifically sound geochemical baseline data that enhance the rationality and transparency of decision-making.

02.7

Novel, In-Situ, Deposit-Scale Mineral System Characterization Methods of the Korsnäs Unconventional REE Deposit, Finland

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In-situ, non-destructive mineral characterization technologies—Laser Induced Breakdown Spectroscopy (LIBS), Hyperspectral Imaging (HSI), and scanning micro-XRF—are increasingly important for critical mineral exploration (Rifai et al. 2018; Jolis et al. 2025). These methods enable continuous acquisition of chemical and mineralogical data directly from drill core while also capturing textural, grain size, and alteration information essential for early-stage resource and geometallurgical evaluations.

This study applies fast LIBS and scanning micro-XRF to characterize the complex Korsnäs REE deposit in Finland. Large-chamber low-vacuum Scanning Electron Microscopy (LV-SEM) complements these methods by verifying fine-grained, chemically complex minerals. Allanite-group minerals challenge traditional HSI due to weak VIS-NIR absorption, but their high REE content allows LIBS and micro-XRF to detect and map REE minerals quantitatively using spectral angle mapping (SAM) and Automated Mineral Identification and Characterization System (AMICS) algorithms. LIBS was used in continuous imaging mode across mineralized intervals, while micro-XRF and LV-SEM were conducted on selected core pieces to produce high-resolution elemental and mineral mapping for validating LIBS results.

Our investigation identifies Korsnäs as a world-class example of unconventional REE mineralization: a carbonatite–antiskarn system with two distinct ore types. 1) **Carbonatite vein-hosted apatite ore**, dominated by REE-apatite and REE-fluorocarbonates, occurs with hyalophane pegmatite, barite, and altered ultramafic dykes. Apatite varies from mm to 10 cm in grain size, is chemically heterogeneous, and contains 10–90% inclusions of REE-fluorocarbonates and monazite. Galena, historically mined until the 1960s, occurs in trace to significant amounts. 2) **Antiskarn-hosted allanite ore**, recently discovered by Prospect Ltd., comprises bands and acicular aggregates of poikiloblastic allanite with titanite as a secondary REE-host. The matrix comprises calc-silicate minerals (pyroxenes), minor carbonates, and hyalophane.

Our integrated workflow demonstrates the potential of LIBS and micro-XRF for rapid, quantitative REE mineral mapping in complex deposits, supporting early-stage evaluation and geometallurgical modelling, while providing the components required for Mineral-system modelling at a deposit scale; host lithology, alteration, ore mineralogy and structures.

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02.8

Gangue mineralogy of the Leveäniemi iron oxide-apatite deposit, Svappavaara area, northern Sweden

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The Leveäniemi iron oxide-apatite deposit is one of three deposits currently in production by Luossavaara Kiirunavaara AB in northern Sweden. The gangue mineralogy at Leveäniemi is similar to that of the well-known Kiirunavaara deposit, but more complex with regards to textural and mineral chemical variability of amphiboles and other gangue minerals. The dominant ore mineral is magnetite. The beneficiation process faces challenges with increased alkali, silica and magnesium contents in the magnetic concentrates and the final pellet products. The main reasons are magnetite inclusions in grain sizes <40 µm in gangue minerals, and fine iron ore-gangue intergrowths. Representative samples of drill cores were studied by optical and electron microscopy and EPMA (Friberg 2025). Gangue minerals in approximate decreasing abundance are: Ca-amphibole, apatite, carbonate, quartz, clinopyroxene, biotite, chlorite, scapolite, Mg-Fe-amphibole, epidote, and small amounts of titanite, allanite, talc, feldspar, clinozoisite, and serpentine. There are also some unknown secondary phases, with chemistries close to various clay minerals. Petrographic observations have revealed intimate intergrowths of magnetite with various gangue minerals, particularly amphiboles and mica.

All Ca-amphibole is Mg-dominant ($Mg/(Mg+Fe) > 0.5$) but show a large variation in composition for Na, K, Al, and Ti, ranging from tremolite to pargasite/edenite/magnesiohastingsite. Clinopyroxene is mostly Mg-dominant. Also, the biotite is Mg-dominant with $Mg/(Mg+Fe)$ between 0.6-0.9, and some octahedral Al. Chlorite is quite variable in composition but always below $Fe/(Fe+Mg)=0.5$. Scapolite is slightly dominated by the marialite component (Na-Cl over Ca-CO₃) but with significant SO₃. Apatite is F-dominated, with significant Cl up to 2.7 wt%.

Amphibole is the main source of Mg to the final ore concentrate and also contributes with minor Na and K, while the mica provides most of the K. Scapolite and feldspar add significantly to the Na-budget, while the minor silicates add to the levels of mainly Mg and Si. The findings potentially enable improved stockpiling and more stable downstream processing.

The general metamorphic grade is uncertain. However, the ore appear to have experienced hydrothermal overprinting, adding Cl, CO₂, and SO₃, generating scapolite and possibly changing the composition of apatite. This has been related to fluids released by metamorphism of evaporites (e.g., Bernal et al. 2017). A low T alteration formed clay minerals and secondary phosphates.

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O2.9

Gathering Nd isotope fingerprints of REE deposits in the REMHub project: towards ore-to-magnet geotracerability

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Europe's drive for a secure and responsible supply of critical raw materials has created a need for provenance verification of neodymium used in permanent magnets. Traditional document-based chain-of-custody systems are vulnerable to tampering, whereas geochemical signatures could offer a scientific, tamper-resistant alternative to link manufactured products back to their source deposits.

Within the REMHub project, we are evaluating neodymium isotopes as tracers along the ore-to-magnet pathway. Nd isotope systematics, governed by the radioactive decay of ¹⁴⁷Sm to ¹⁴³Nd and expressed in epsilon notation as $\epsilon^{143}\text{Nd}$, primarily reflect mantle vs. crustal sources of various REE ore occurrences. Importantly, radiogenic Nd isotope ratios vary between deposits, and they are assumed to remain relatively unaffected by beneficiation and metallurgical processing, whereas mineralogical and most elemental characteristics are lost during these steps.

We are currently collecting *in-situ* Nd isotope data from REE occurrences in Estonia (phosphorites of Ülgase, Aseri and Toolse), Finland (Korsnäs, Sokli, Otanmäki and Kiviniemi), Sweden (Norra Kärr), and Greenland (Kringlerne) to assess their distinctiveness and intra-deposit variability. Furthermore, to evaluate tracer stability, we will analyze Nd isotopic compositions of metallurgical concentrates and metals processed from the Korsnäs ore and recycled Nd from magnet scraps. We aim to provide a critical test of Nd isotope fingerprints as a foundation for Nd geotracerability.

To date, 216 spots of LA-MC-ICP-MS *in situ* Nd isotope analyses have been done on apatite from Estonian phosphorite occurrences. The six samples analyzed show minimal Nd isotope variation between these spatially associated deposits. The mean of all analyses, $\epsilon^{143}\text{Nd(T)}$ of -7.0 ± 4.8 (2 σ), aligns with estimates of Ordovician seawater $\epsilon^{143}\text{Nd(T)}$ for Baltica ($\epsilon^{143}\text{Nd(T)} = -6.93 \pm 0.29$, 2 σ ; Leetse Formation; Wright et al. 2002). These negative values contrast with many (although not all) carbonatite REE occurrences, which often have positive $\epsilon^{143}\text{Nd(T)}$ (Bell & Simonetti 2010). Apatite being the only Nd carrier phase in Estonian phosphorites may favor isotopic stability throughout mineral beneficiation. In retrospect, old REE deposits with variable ¹⁴⁷Sm/¹⁴⁴Nd ratios across mineral phases—such as Korsnäs, where REEs occur in allanite, apatite, monazite, titanite and bastnäsite-synchysite—are expected to show mineral-dependent $\epsilon\text{Nd(0)}$ values. How these signatures persist through processing remains to be seen.

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O2.10

Application of stable and radiogenic isotopes in critical raw materials traceability: case studies from sulphur, lead and nickel isotopes

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As we advance the transition to low-carbon energy to address climate change, the need for critical metals, minerals, and raw materials is surging and will continue to rise due to their key role in key technologies. Ensuring the traceability of these critical raw materials has become crucial in promoting responsible sourcing and sustainable practices throughout the supply chains. However, modern supply chains are complex and lack transparency, which requires technological development of novel traceability systems.

Advances in the mass spectrometry instrumentation, particularly in multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) allow for high-precision isotopic analysis, not only for the traditional stable isotope systems, like sulphur (S) but also for the non-traditional isotope systems, such as lithium (Li), iron (Fe), silicon (Si) and nickel (Ni). Previous studies have demonstrated great potential of using isotope ratios for traceability in modern complex supply chains. e.g. using stable Li isotopes in tracing the sources of Li in Li-ion batteries (Desauty et al. 2022) and radiogenic Nd isotopes for tracing rare earth elements in permanent magnets (Liu et al. 2024). Here, we present a study focusing on tracking the source of nickel and cobalt (Co) from magmatic Ni(-Co) sulphide ores by using S, Pb and Ni isotopes and investigating their isotope fractionation during the successive extraction processes. Our results show that S and Pb isotopes are highly promising in distinguishing different magmatic sulphide ores due to the characteristic signatures of individual deposits or regions. The S isotopic signature stayed robust during pyrometallurgy (smelting) process but changed during the latest hydrometallurgy stages (Solvent Extraction). Multi-sources of the smelted Ni product (Ni-Co matte) can be captured by Pb isotopes since little fractionation would occur during the metallurgical processes (Cui & Wu 2011). Compared to S isotopes, Ni isotope compositions are lower but its isotope ratios also show notable variation among different magmatic sulphide ores ($\delta^{60/58}\text{Ni}$ from -1.69 ‰ to 0.58 ‰). The analytical protocol for Ni isotopes in product samples (e.g., Ni-Co matte and Ni sulphate) is currently under development at the Espoo research laboratory of GTK and whether there is fractionation during the Ni extraction processes from the ores will be reported later.

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02.11

Gypsum treatment on acid sulfate soils in W Finland

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Farmlands on fine-grained postglacial clay soils in SW and S Finland are highly susceptible to erosion and P loss. Previous studies have shown that gypsum treatment reduces both particulate and dissolved P in runoff (Uusitalo et al. 2012), without harming plant nutrition or soil chemistry (Yli-Halla et al. 2023). Gypsum increases the ionic strength in the soil solution, provides Ca²⁺ to bridge soil particles and form larger aggregates, thus reducing erosion and P loss (Ollikainen et al. 2020).

Recently, significant areas of acid sulfate soils (ASS) in W Finland have been treated with gypsum, although little is known about its geochemical effects on these soils. ASS are a worldwide environmental problem, due to oxidation of sulfidic compounds forming H₂SO₄, leading to acid soils (pH <4) and leaching of toxic metals. Accelerated leaching of toxic metals from cation exchange sites due to excessive Ca²⁺ from gypsum is a potential risk, adversely affecting water quality and aquatic life. In addition, ASS suffers from very little erosion and P loss, making gypsum treatment of these soils likely unnecessary.

The objective of this study is to assess how gypsum treatment influences the transport and mobility of toxic metals, SO₄, and nutrients in ASS, through the water flow path from the topsoil to the subsoil, and ultimately to the recipient stream.

The main hypotheses are:

- (1) Gypsum will increase leaching of metals from cation exchange sites in ASS.
- (2) SO₄ will be rapidly leached throughout the whole soil profile and temporarily cause SO₄ concentrations to rise in recipient streams, but negligible amounts compared to background levels.
- (3) The soil nutrient balance will not be significantly harmed.

For this study, six pairs of two-meter-deep soil profiles were taken, from adjacent gypsum-treated and reference ASS farmlands, in Laihianjoki river catchment, W Finland. Easily soluble, cation exchangeable, and near-total element concentrations of the soil samples were obtained by extracts of water, KCl, and aqua regia, respectively. Water samples were collected from recipient subsurface drainage pipes, recipient tributaries to the main river, as well as the river mouth.

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02.12

Embrace Error, Embrace PROMACE – Introducing Propagated Mass Change Error

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Mass change calculations, proposed by (Gresens 1967) and developed upon by (MacLean & Barrett 1993), are used for several applications, such as ore vectoring (Fahlvik et al. 2022), research on global biogeochemical cycles (Coggon et al. 2016), and assessment of geothermal systems (Toro Vivanco et al. 2024). All these workers acknowledge the limitations of the method; however, only 23% of papers published since 1994 report mass changes calculation errors. A minority of these apply a formal approach to quantifying combined errors, and this is usually done for the single precursor technique (Gresens 1967). Only one paper (Coggon et al. 2016) has done this for the multiple precursor technique of MacLean & Barrett (1993). Thus, we propose applying propagated mass change error (PROMACE) on mass change calculations.

The PROMACE method quantifies the combined error for: 1) sampling and analysis, 2) modelling fractionation and alteration, and 3) uncertainty in the choice of least-altered rocks. To do this, formal error propagation on the mass change equation (Gresens 1967; MacLean & Barrett 1993) is applied, where the partial derivatives of each variable in the equation are used to weight individual error contribution. Through using PROMACE, it is possible to evaluate the impact of each individual error source. Additionally, by quantifying combined errors it is possible to define significance thresholds for each element affected by mass changes, where only mass changes exceeding twice the propagated error are considered significant. The use of PROMACE is demonstrated in variably altered host rocks to multiple volcanic massive sulphide deposits, including Rävliiden North, Svärdsjö and Saxberget. PROMACE provides a framework to strengthen interpretation and reproducibility, and to support adoption we present a freely available R (version 4.4.1) application for mass change calculations in variably altered rocks.

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P2.1

Utilizing historical geochemical datasets to create proxies for REE mineralization in the Sokli carbonatite complex, northeastern Finland

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The Sokli carbonatite complex (ca. 365 Ma) is part of the Devonian Kola Alkaline Province in the northeastern Fennoscandian Shield. Its magmatic carbonatite-rich core is surrounded by metasomatic carbonatites and ultramafic silicate rocks, followed outwards by a transition zone dominated by amphibole- and pyroxene-rich rocks, and finally by a fenite aureole. The whole Sokli area is covered by weathered bedrock and glacial till of variable thickness (O'Brien & Hyvönen 2015). Weathering has produced extensive laterite layers, which have been historically the main economical point of focus at Sokli due to their high phosphate concentrations. In recent years, the potential of other ore types in Sokli has been more actively investigated; these include magmatic phosphorite-hosted Nb and late carbonatite dyke-hosted REE mineralization.

Various types of sampling have taken place in the Sokli area in numerous campaigns starting from the 1960s. The aim of this study was to evaluate the historical assays from the Sokli area and process them to create proxies for the occurrence of REE-rich carbonatite dykes. All available geochemical data can be combined into four datasets based on the assayed material: fresh bedrock, partially weathered rocks with varying degrees of hardness and cohesion (PWR), fully weathered laterite, and till cover.

The fresh bedrock dataset was used to establish the geochemical signal of the REE-rich carbonatite dykes. The dykes are enriched in REE, Ba, Sr, Zn, Mn, Ag and Th, and depleted in Ta, V, Zr, Al, K, Si, Ti and Cr compared to all other rock types; Cu, Co, Fe and Mg are also enriched compared to other carbonatites. A statistical comparison of assays from different sampling campaigns within the PWR, laterite and till datasets reveals no major differences for most elements. Some variation is explained by differences in the underlying geology of the zoned complex. Results of Spearman rank correlation and principal component analysis highlight different elemental associations representing the geochemical signal of the REE-rich dykes in the PWR, laterite and till datasets. In PWR, REE, Sr, Ca, Mn, and Zn best describe the dyke signal; Ba does not correlate with them and is considered a weak proxy in this dataset. In laterite, REE, Sr, Ca, Zn, Ag, Co, and less so Ba and Cu, represent the dyke signal. In till, La, Sr, Mn and subordinately Cu are part of the dyke-related signal. The identified elemental associations can be utilized as proxies in mineral prospectivity modelling targeting the REE-rich late carbonatite dykes. This study shows that careful processing of historical geochemical datasets by combining statistical analysis with geological knowledge can extract useful information that could be utilized in mineral exploration.

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P2.2

(Bio)geochemical Dynamics of Seawater-Aquifer Interactions: Impacts on Coastal Sediments and Ecosystem

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Coastal aquifers are dynamic transition zones where fresh groundwater and saline seawater interact. In the Baltic Sea region, dense coastal populations and groundwater use affect the quality of groundwater, making coastal aquifers both vital resources and vulnerable systems. Excessive groundwater extraction and climate change may make aquifers more susceptible to seawater intrusion, lowering groundwater quality, while submarine groundwater discharges transport nutrients, carbon, and metals to the already vulnerable coastal waters (Burnett et al. 2003; Ferguson & Gleeson 2012; Luoma et al. 2015). These fluxes can strongly influence seabed and water column biogeochemistry, and their magnitude and ecological consequences in the Baltic Sea are not yet fully understood.

We investigate how seawater-aquifer interactions affect groundwater quality, sediment biogeochemistry, and coastal ecosystems in the Baltic Sea. By combining biogeochemical analyses of groundwater and sediment porewater with benthic biodiversity and trait analyses at a coastal aquifer site in Hanko, Finland (Virtasalo et al. 2019), the study will provide one of the first integrated assessments of these linkages in the region. Firstly, we will investigate potential seawater intrusion in aquifers of the Hanko coast, relevant for the protection of water resources. Secondly, we will quantify the impact of groundwater-seawater interactions on coastal sediments and local biota, as well as their relevance for the chemical load in coastal areas with aquifers. This will provide new insights about the effects of coastal aquifers on marine ecosystems and their biodiversity.

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P2.3

Portable analysis method for the low concentrations of gold

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The use of portable geochemical analyzers has become more widespread and diversified in ore exploration. The most used analyzer is the portable, hand-held X-ray fluorescence (pXRF) analyzer, which has been found to be effective in the analysis of both geological samples and metals. For example, in till geochemical ore exploration, pXRF is particularly effective in the analysis of base metals and several major elements (e.g., Sarala et al. 2015; Sarala 2016). Portable analyzers enable the analysis of boulder, rock and soil samples directly in the field, which significantly speeds up the exploration process and improves cost-effectiveness. However, the analyzers have their limitations, as the detection limits can be quite high for several elements and, on the other hand, low concentrations cannot be analysed reliably. Typically, the detection limit is tens to hundreds of ppm depending on the element.

Although pXRF technology has provided an effective way to analyse a wide range of commodities, there are certain elements which analysis is not possible. For example, precious metals such as gold occur in such low concentrations in soil that their analysis cannot be reliably performed with pXRF. Recently, new analytical concept called DetectORE™ was launched and that technology provides fast and practical analysis of low concentrations of Au (even in 5-10 ppb level) directly in the field or field camp. The analytical procedure includes sample preprocessing, 6–24 hours of leaching supported by rotational mixing, leaching solution and collector to adsorb and concentrate Au, and data processing software usable for different portable XRF analyzers (Sarala et al. 2024). More than 30,000 samples and tests have been carried out during the research and development phase using field samples, gold solutions and CRM systems, and the results have proven the method to be effective. This was also supported by the test campaign done in the Oulu Mining School in 2024-2025 for the basal till and weathered bedrock samples from northern Finland. The pXRF and laboratory-based analytical results showed strong correlation in the several Au exploration targets.

Acknowledgments

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03.1 (Keynote)

Unveiling the Deep Biosphere of the Fennoscandian Shield: Ancient Echoes and Modern Activity

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The deep continental crust hosts a vast, resilient, and still enigmatic biosphere. In the Fennoscandian Shield, research in the last decades have revealed compelling evidence of both ancient and active microbial life, reshaping our understanding of subsurface ecosystems. In fact, research of the deep igneous-rock hosted biosphere of the Fennoscandian shield have played a pioneering role in deep biosphere research (Pedersen 1997).

Recent studies have documented ongoing microbial methanogenesis and sulfate reduction in deep bedrock fractures (Westmeijer et al. 2024) supported by isotopic and geochemical signatures. These processes occur down to several kilometers below the surface, where microbial communities interact with long-residence-time fluids and mineral substrates. In addition to modern activity, we have identified fossilized microbial structures and biosignatures in Precambrian rocks and impact craters, indicating episodic colonization over geological timescales.

Impact structures such as Siljan and Lappajärvi provide unique windows into the deep biosphere. At Lappajärvi, our team has recently uncovered evidence of ancient microbial sulfate reduction preserved in hydrothermal veins formed during post-impact cooling (Gustafsson et al. 2025). These findings suggest that impact-generated hydrothermal systems may have sustained microbial ecosystems for extended periods, leaving behind mineralogical and isotopic traces of life.

Emerging concepts such as dark oxygen—oxygen produced abiotically via water-rock reactions—raise intriguing possibilities for sustaining aerobic metabolisms in otherwise anoxic environments. While still speculative, such mechanisms highlight the complexity of deep biosphere energetics.

Despite these advances, the deep biosphere remains one of Earth's least understood ecosystems. Key questions persist regarding microbial dispersal, metabolic rates, and the influence of climate-driven hydrological changes on subsurface life. An intriguing issue is also the role of this deep biosphere in understanding evolution on Earth. As we probe deeper into the crust, we continue to uncover a biosphere that is not only ancient and resilient but also dynamically responsive to geological and climatic forces. This presentation will summarize recent findings from the deep rock-hosted biosphere in general, and the Fennoscandian shield in particular.

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03.2

Evolution of diagenetic minerals in Nam Co, a high-altitude Tibetan lake

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The Tibetan Plateau, with its average elevation of 4000 m above sea level, is the highest plateau on Earth. It is the third largest store of ice after the Arctic and Antarctic, which is why it is sometimes referred to as the Third Pole (Kang et al. 2010). It is an area sensitive to climate shifts and is expected to go through significant warming in the future (Cruz et al. 2007).

To better predict the effects of future climate change, the past climatological conditions of these regions are studied through paleoenvironmental proxies. Lake sediments act as paleoenvironmental archives; minerals forming in the water column record the prevailing environmental conditions during deposition (Gebregiorgis et al. 2020). However, post-depositional processes such as early diagenesis cause alteration in mineralogy, structure and/or chemistry of deposited sediments. This happens through the action of compaction, fluid circulation and physico-chemical changes, often mediated by microbial activity *in situ*.

In this study high-resolution X-ray computed micro-tomography (μ CT) images, combined with X-ray fluorescence scanning, and geochemical analyses are used to study early diagenetic formation of iron sulphides (pyrite) in Lake Nam Co, a large, high-altitude lake in the Tibetan Plateau. μ CT images capture the evolution of pyrite grains within a 69 cm long gravity core. Low-resolution CT scans of the whole core show presence of bioturbation burrows throughout the core. With increasing core depth, the burrows are gradually filled with framboidal pyrite clusters.

These findings have important implications for interpreting the sediment archives of Lake Nam Co. Preliminary pore water data indicate that sulphate is being removed from the aqueous phase and immobilised in the sediments as pyrite. This is supported by an increase in sulphur content of the sediment, which is observed in both XRF and total sulphur analyses. Given that the pyrite is formed shortly after deposition, it could be suitable for tracing changes in the basin-wide sulphur isotope composition, which could be driven by climate.

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03.3

Insights into microbial sampling of ultra-low biomass, ultra-deep, hypersaline fluids in Otaniemi, Finland

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In the efforts to find new, environmentally friendly means for district heat production, two ultra-deep production wells were drilled in Otaniemi, Finland, reaching depths of approximately 6 km. At this depth, the fluids are saline, reaching 200 g L⁻¹ TDS, anoxic, approximately 100°C hot and experiencing a hydrostatic pressure of 500 bar. The fluids are slightly alkaline and oligotrophic but contain CH₄ and H₂.

In an effort to study the microbiological composition of these fluids, samples were collected using a positive displacement sampler operated by ICDP's Operational Support Group (OSG) in September, 2024. The sample volumes were ~600 mL/sample. The sampler was cleaned with 70% ethanol and rinsed with sterile MilliQ water. Contamination control samples were collected by filling the samplers with sterile water and collecting and treating the control sample in the same way as the actual samples. Contamination control samples were also collected from the water-glycol solution and mineral oil used for the sampler operation. The samples were studied by epifluorescence microscopy, DNA was extracted by first collecting the biomass on 0.1 µm pore-size filters and the filtrate was additionally precipitated with PEG. The microbial communities were characterized by qPCR, amplicon sequencing and metagenomics. In addition, cultures targeting heterotrophic and autotrophic thermophiles were set up from all samples in anaerobic infusion bottles.

The first results indicate that even low-level contamination from reagents, equipment and sample handling is detrimental to the study. The amount of indigenous microorganisms was < 5 bacterial 16S rRNA gene copies mL⁻¹ measured from the 0.1 µm pore-size filter DNA extraction, whereas the contamination control (MilliQ water) contained between 160 – 380 gene copies mL⁻¹. The filtrate, i.e. <0.1 µm sized cells, the copy numbers were 17 – 86 mL⁻¹, whereas the MilliQ contamination control samples contained 15 – 21 bacterial 16S rRNA gene copies mL⁻¹. Epifluorescence microscopy corroborated the results. Amplicon sequencing showed a high proportion of contamination from sampling equipment, sample handling and laboratory reagents. Stringent curation of the data by removing all typical human contaminants and all taxa present also in the contamination controls, revealed a bacterial community mostly consisting of members of the Patescibacteria phylum. These bacteria are ultra-small and are often found in deep groundwater environments. Our study is the first to show Patescibacteria as the dominating component of the community in ultra-deep, hot, saline fluids, although their numbers are low. Culture based and metagenomic analyses are ongoing to reveal the first clues to the metabolic capacities of this phylum.

03.4

From Debris to Dynamic Interface: How the Plastisphere Shapes Ecosystems and Health

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In aquatic environments, plastic debris provides novel surfaces for microbial colonization, giving rise to the *plastisphere*: a biofilm interface that mediates plastic degradation, stability, and transport across ecosystems. Far from inert, the plastisphere incorporates organic matter, metals, minerals, and salts from its surroundings, creating a biogeochemically reactive substratum that links plastics to broader elemental cycles.

Recent studies show that plastisphere communities not only degrade and disperse plastics but also drive mineralization and metal cycling. Metals and minerals embedded within biofilms act as nucleation sites and redox-active catalysts, serving as electron donors and acceptors in microbial metabolism. These processes foster biomineralization, alter plastic stability, and amplify opportunities for horizontal gene transfer, including the spread of antibiotic resistance genes—an emerging risk to environmental and human health.

Here, we present new work characterizing the biotic and abiotic composition of the plastisphere and tracking the biogeochemical functions of plastic-associated microorganisms. Combining microbiology, mineralogy, geochemistry, and advanced imaging, we develop novel approaches to study this dynamic interface and its influence on microbial processes across redox regimes. Laboratory and field-based investigations in Denmark, Greenland, and Tanzania reveal how plastics move through sedimentary environments, operate across size scale, interact in the complex geochemical settings of water and sediment, shape biological activity, and emerge as a growing health concern.

03.5

From plastic pollution to carbon cycling: the role of aquatic fungi in coastal sedimentary systems

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Microorganisms play a central role in the degradation of organic matter and the balance between carbon storage and CO₂ release in aquatic systems. Plastics add a novel, anthropogenic carbon pool to the biogeochemical cycles that govern carbon drawdown, respiration, transport, and storage across atmosphere, water and sediment domains. Plastics are quickly colonized by microorganisms in the environment, forming a biofilm named the *plastisphere*. The *plastisphere* is complex, consisting of, i.e., diverse bacteria, fungi, diatoms, as well as salts, minerals and metals reflective of the host environment. Through their metabolic activity, some microorganisms in the *plastisphere* mediate plastic transformation into CO₂ or biomass. Fungi are universal decomposers, with specialized enzyme systems for recalcitrant polymers such as lignin and chitin. These capabilities position them as key players in plastic polymer transformation, influencing the fate of plastics in the natural environment. Yet, the role of aquatic fungi on plastics remains largely understudied, particularly regarding their diversity, ecological functions, and contribution to carbon cycling, transport and storage.

To address this gap, we deployed two plastics, the conventional plastic polyethylene (PE) and the bioplastic polylactic acid (PLA), for two months along the freshwater, brackish, and marine transect of a Danish estuary. The plastics were placed in water columns, sediments, and rhizospheres to test how habitat and root-associated processes influence fungal colonization and plastic degradation. In current and future work, NanoSIMS will track carbon assimilation in individual fungi isolated from the system, revealing fungi as overlooked agents in the environmental fate of plastics. By coupling plastic degradation to sedimentary carbon fluxes, aquatic fungi may influence whether plastic-derived carbon is respired, recycled, or sequestered in sediments. Understanding these processes is essential to refine our models of the coastal carbon cycle.

03.6

Sedimentary Carbon Stocks and Microbial Turnover Assessment in Shallow Coastal Areas of the Baltic Sea

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Coastal sediments play an important role in the global carbon cycle. Bathymetric depressions on the continental shelves are known to accumulate fine grained organic rich material, removing carbon from biogeochemical cycles in the water column and acting as long-term carbon sinks. However, the relative importance of shallow near-shore settings as carbon sinks is yet to be explored. Such areas are naturally heterogeneous and strongly affected by anthropogenic perturbations. The carbon sink capacity of near-shore sediments is expected to be shaped by topography, remineralisation dynamics and the quality of organic matter/carbon along with other environmental and depositional factors. Sediments in such settings receive relatively fresh and labile organic matter from various marine and terrestrial sources, that may be either buried *in-situ* or transported to deeper areas over time. To investigate the factors controlling carbon stocks and turnover in complex near-shore settings, we quantified the spatial distribution of dissolved and particulate carbon in sediments over a strong gradient of salinity, wave exposure and organic matter sources in shallow locations (3–4 m water depth) in the coastal zone of the Hanko Peninsula (Finland). We studied four zones: sheltered estuary, sheltered archipelago, semi-sheltered archipelago, and exposed shoreline, in each case determining sediment carbon stock and microbial turnover as a fraction of the stock. We observed the highest carbon stocks ($\sim 4000 \text{ g C m}^{-2}$ in the uppermost 25 cm) in sheltered environments associated with low wave energy systems (sheltered estuary and sheltered archipelago). Consequently, we observed a moderate positive correlation between the mean sediment grain size and depth-attenuated wave exposure (Virtanen et al. 2019). In contrast, exposed shoreline areas were generally sandy and had carbon stocks one to two orders of magnitude lower than in the sheltered locations. Using porewater profiles to estimate diffusive fluxes of dissolved inorganic carbon, methane and dissolved ammonium, we observed low (max 5% from upper 10cm sediments) but variable rates of carbon turnover between the sampling locations, expressed as a fraction of the stock demineralised in a one-year period. Overall, our study highlights the importance of sheltered near-shore sediments in the carbon budget and dynamics of this coastal system and underscores the need to capture small-scale spatial heterogeneities when quantifying the fate of organic carbon in coastal settings.

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03.7

As- and Cd-concentrations in surface sediments in the Barents Sea: The role of early diagenetic and organic matter bacterial degradational processes

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Arsenic (As) and cadmium (Cd), two toxic (carcinogenic) chemical elements are present in the Barents Sea marine sediments. Geochemical analyses of sediment samples shows there are marked differences with depth in concentrations in the top few centimeters for both As and Cd. The presence and concentration of As and Cd in the marine sediments is relevant for the toxicological conditions in the sediments, and for the biota, which can take up As and Cd from the sediments.

Samples and geochemical analyses are based on the MAREANO mapping program (2005 - ongoing), where pollution chemistry is one topic. Samples presented include samples from Institute of Marine Research (IMR) in 2003 and 2004, covering large parts of the Norwegian part of the Barents Sea.

Analysis of sedimentary parameters of 1 cm sediment slices include grain size (% mud content), TOC (total organic carbon in weight %), TS (total sulphur content in weight percent), and geochemical element analysis including As, Cd, Mn and Fe and Pb²¹⁰ dating to obtain sedimentation rates.

Analytical data from sediment cores show there is a marked enrichment of As in samples close to the surface compared to deeper levels, i.e. some cms below the surface. Maximum concentration is either at the surface or 2-3 cms below the surface. Cd shows the opposite pattern compared to As: there is a decrease in concentration in the upper cms of the sediments, and often the concentration is below LLD (Lower Level of Detection). As-concentrations reach class III (moderate pollution) or IV (polluted) according to the Norwegian pollution classification for marine sediments. The highest levels As-concentrations are around Svalbard and in the South-eastern part of the Norwegian part of the Barents Sea. The redox processes leading to increase in As-concentration in the top few cms are related to biogeochemical processes within the sediments caused by bacterial degradation of organic matter. As-enrichment in the top 3 cms is in the range of 5 times the As-concentration in underlying sediments. Geographical differences in As-concentrations in surface sediments are the result of different concentrations in As in the sources of the sediments. Eroding Tertiary sedimentary rocks on Svalbard have higher As-concentrations compared to other stratigraphic intervals.

Cd, generally present in low concentrations in the Barents Sea sediments, shows the opposite change in concentration in sediments towards the surface as compared to As, i.e. a marked reduction from deeper sediments to the surface. The decrease in Cd-concentration in sediments is probably related to formation of Cd in soluble form, and probably more available for benthos within the sediments.

03.8

Tracing Natural and Anthropogenic Influences on Riverine Iron & Manganese Transport in Northern Sweden

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Iron (Fe), originating from the weathering of terrestrial rocks and transported via rivers, is a vital nutrient for the marine biosphere. Its mobility and speciation depend strongly on redox conditions, organic matter interactions, and hydrological regimes. In Sweden and Finland, many rivers are characterized by high suspended loads of Fe and manganese (Mn), strongly influencing their elemental abundance and geochemical cycling in the Baltic Sea. Many of the rivers, however, are dammed for hydropower generation. Damming alters natural hydrology by creating artificial reservoirs, modifying residence times, and perturbing surface water–groundwater interactions. While such regulation has been shown to reduce Si fluxes to the Baltic Sea by ~25% (Humborg et al. 2006), the impacts on Fe export remain less well constrained.

To address this gap, we sampled river water from the heavily regulated Lule River and the unregulated Kalix River in April and September 2025, representing contrasting hydrological and seasonal conditions. A two-step filtration approach was applied to separate particulate (>0.2 µm), colloidal (0.2 µm–3 kDa), and truly dissolved (<3 kDa) fractions. Concentrations of Fe, Mn, and associated elements and organic content were determined in each size fraction to evaluate differences in metal speciation and transport between pristine and dammed catchments.

Results from the first river sampling campaign in April 2025 show apparent differences between pristine and regulated rivers and the concentrations of Fe and Mn associated with colloidal and dissolved fractions. The Kalix River shows generally higher Fe concentrations compared to the Lule River, especially towards the river mouth where lower pH values were measured. Higher Fe concentrations (2.6–560 ppb) were detected in the colloidal fraction that are up to 20 times higher than that in the dissolved fraction (1.3–45.3 ppb). In contrast, Mn concentrations were 5 to 13 times higher in the dissolved phase (0.2–14.9 ppb) compared to the colloidal phase (0–2.5 ppb). Our preliminary results support findings from previous studies from the unregulated Kalix River (e.g., Ingri et al. 2006) that Fe–C colloids, originating from wetland and forest areas, dominate Fe transport. The effect of one of the biggest dams (Porjus kraftverk) in the Lule River becomes evident: colloidal Fe decreases by 70% from 20 ppb before the dam down to 5.2 ppb after the dam. Our study will thus provide new insights into how anthropogenic regulation modifies these natural seasonal patterns of Fe transport in the Northern Baltic Sea catchment.

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03.9

Microbial community structure and adaptation in naturally metal-enriched soils in Northern Finland

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Microbial communities are highly sensitive to elevated concentrations of arsenic and metals in their environment. Certain microbial taxa have evolved specialized metabolic mechanisms that enable them to tolerate, transform, or even utilize these elements. In natural ecosystems, microbes can play a critical role in supporting plant growth under geochemically stressful conditions by enhancing the availability and facilitating uptake of nutrients and producing plant hormones that promote growth.

This study investigated the microbial diversity of microbes in the soils with naturally elevated concentrations of arsenic and metals in areas surrounding mining activity or mineral potential. The aim of the study was to identify microbial taxa that have adapted to the high metal concentrations and to elucidate the environmental factors shaping microbial community composition in northern Finnish soils. Nine study sites were selected across northern Finland: Ikkari, Sakatti, and Pahtavaara in Sodankylä; Kuotko in Kittilä; Pampalo and Rämepuro in Ilomantsi; Sokli in Savukoski; Kaustinen, and Suomussalmi municipalities. A total of 102 soil samples were analysed extensively for their geochemical and physical properties as well as their bacterial and fungal community profiles.

The relationships between the microbial communities and geochemistry, including the naturally high concentrations of metals, were examined.

Kuotko and Pahtavaara sites, both associated with gold mineral deposits, exhibited elevated concentrations of metals and arsenic compared to typical Finnish soil parent material. In Kuotko, geochemical baseline studies show that As, V, Co and Ni in the soil had higher concentrations than the typical soil. In Pahtavaara area, also Cr had higher concentrations in the soil samples. Proteobacteria dominated the bacterial communities with Xanthobacteraceae, Oxalobacteraceae, and Nitrosomonadaceae being the most prevalent. Kuotko soils showed the highest microbial diversity (median Shannon H' 5.25). However, a non-metric multidimensional scaling (NMDS) analysis revealed Cu concentrations the most significant environmental factor affecting bacterial community structure in Kuotko, while Cr and Ni had the greatest impact in Pahtavaara. Ongoing analyses aim to further characterize microbial community responses and their implication for vegetation development in mine waste cover solutions in cold climate. These findings contribute to a deeper understanding of biogeochemical resilience and microbial ecosystem services in metal-rich soils. The research is part of the Biopeitto 3 project, funded by the European Regional Development Fund (ERDF) via the North Ostrobothnia ELY Centre with additional support from Mawson Oy, Hannukainen Mining Oy, Boliden Kevitsa Mine Oy, Rupert Resources Oy, AA Sakatti Mining Oy, Agnico Eagle Oy, Kittilä and Sodankylä municipalities, GRK Oy, Neve Oy and Levin vesihuolto Oy.

P3.1

Quantitative assessment of sulfate-reducing bacteria in acid sulfate soils: Linking microbial activity to corrosion risk

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Acid sulfate soils (ASS), formed from sulfide-bearing postglacial sediments in Finland's coastal regions, pose significant environmental and geotechnical challenges. Upon disturbance, these soils oxidize and produce sulfuric acid, leading to low pH and mobilization of metals. In addition to environmental risks, ASS environments accelerate corrosion of infrastructure materials due to their acidity, high electrical conductivity, and microbial activity.

This study investigates sulfate-reducing bacteria (SRB) in ASS environments, focusing on their role in microbiologically influenced corrosion (MIC). SRBs thrive under anaerobic conditions and produce hydrogen sulfide, which promotes the formation of corrosive compounds and biofilms. We apply quantitative PCR (qPCR) targeting the functional marker gene *dsrB* to quantify SRB abundance across four distinct test environments:

1. **Aged steel and concrete structures:** Soil adjacent to long-standing steel and concrete structures exposed to ASS conditions was sampled aseptically to investigate long-term corrosion and microbial activity.
2. **Laboratory corrosion test:** Black iron rods were incubated in homogenized ASS and reference non-ASS soils, and for DNA extraction, soil and corrosion product samples were collected at 2 and 6 months of incubation. Corrosion progression was assessed using microscopy and X-ray computed tomography.
3. **Field-scale corrosion test:** Cast iron samplers were installed at three depths (0–3 m) across four sites in North Ostrobothnia. After one year, samplers were retrieved and soil was aseptically sampled from upper and lower sections near the metal surface. Corrosion product–soil mixtures were also collected.

Following the aseptic sampling, DNA was extracted using the DNeasy PowerLyzer PowerSoil Kit (Qiagen) and stored for qPCR analysis. This protocol was consistently applied across all samples.

The qPCR-based quantification of *dsrB* will provide insight into SRB distribution and activity, enabling correlations with geochemical parameters (pH, EC, sulfate, chloride) and observed corrosion effects. This integrated approach—combining microbial, geochemical, and material degradation data—aims to improve understanding of corrosion mechanisms in ASS environments and support predictive tools for infrastructure risk assessment.

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P3.2

Deep Life Under Pressure: Hydrogen Formation and Microbial Signatures in Precambrian Crystalline Bedrock

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Fluids residing within Precambrian fractured bedrock are rich in gases such as hydrogen (H₂), helium (He), and methane (CH₄). Among these, H₂ is especially important, serving both as a major energy source for microbial communities in the deep biosphere and as a potential resource in the green energy transition. Within the crust, H₂ can be generated through various processes, including radiolysis and serpentinization. Additionally, in tectonically active zones, mechanical shearing of silicate-containing rocks can form H₂. H₂ released from shearing can substantially boost microbial metabolism, potentially increasing deep biosphere activity by several orders of magnitude and therefore shaping subsurface biogeochemical cycles.

This project aims to advance knowledge of H₂ generation and its role in supporting deep biosphere ecosystems within a previously unexplored setting, i.e. seismically active zones in Precambrian bedrock. We performed fluid and gas sampling down to 5 km depth at Otaniemi deep boreholes in Finland, taking samples for chemical and isotopic composition of water and gases, as well as for microbial signatures. The boreholes were originally drilled for geothermal energy production, but the project was discontinued due to low hydraulic conductivity. Still, these deep boreholes offered a unique opportunity to investigate how hydraulic stimulation, and the resulting induced seismicity might affect H₂ formation within highly saline deep crustal fluids, with implications for the deep biosphere. The temperature at 5 km depth was ~100°C, hydrostatic pressure > 500 bar and total dissolved solids ~200 g/l, conditions that are expected to be extreme for life. Nevertheless, even under these conditions we expect to find signatures of microbiological activity.

The analysis of free gas from the boreholes showed concentrations of up to 26% H₂, 6% He, and 3% CH₄. The results of stable isotope analysis for CH₄ indicate that biogenic methanogenesis is taking place even under these extreme conditions, with H₂ probably serving as the microbial energy source. These findings suggest that (induced) seismic activity affects water-rock interactions, fluid composition, H₂ production, and microbial communities, which are expected to differ from those previously observed in seismically inactive Precambrian settings.

P3.3

Searching for a needle in a haystack - Sampling the ultra-low biomass deep subsurface environment for microbiology from the ultra-deep drillholes in Otaniemi, Finland

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A unique geothermal energy pilot site in Otaniemi, Finland, hosts 2 ultra-deep drillholes extending to over 6 km in depth. The site, built for testing an enhanced geothermal system, was opened for scientific exploration in fall 2024, as groundwater and gas samples were retrieved with an extensive sampling operation combining geochemistry and microbiology perspectives. This initiative aimed to advance the understanding of the dynamics of microbial life and biogeochemical processes occurring at significant depths beneath the surface of this ultra-low biomass deep bedrock environment.

The sampling campaign targeted the OTN2 and OTN3 drillholes, just below the 5 km depth. As the temperatures at these depths are > 90°C, this represents extreme living conditions for microbes. Extremes did not end there, as living this deep also means coping with high pressure, high salinity, darkness, poor nutrient conditions, and low carbon availability. The sampling was done with positive displacement samplers (PDS), with the maximum sample volume of 0.6 liters each. Microbiology samples were divided for molecular biological, microscopical analyses (DAPI) and anaerobic culturing efforts.

Microbiological sampling from ultra-low biomass environments needs to be planned extra carefully to account for possible contamination sources originating from sampling. In this case, control samples were taken as sterile Milli-Q water was circulated through the samplers after ethanol and sterile water wash steps. Additionally, mineral oil and a water-glycogen mix were taken from the PDS equipment. Samples were first filtered on 0.1 µm pore-size filters whereafter the filtrate was precipitated with polyethylene glycol (PEG), in case potential microbial cells had ruptured due to the release of pressure during sampling. Control samples to verify contamination sources arising from the laboratory environment, chemicals and commercial kits were taken, and contaminant lists for typical contaminants arising, e.g., from human sources were identified.

The estimation based on microscopy and qPCR results indicated that the number of microbes, dead or alive was extremely low. After processing the molecular biological samples, contaminant tracking analysis was performed for bacterial amplicon sequence libraries. The analysis indicated different contaminants arising from the samplers, used chemicals, and human sources, but allowed identification of the deep subsurface communities after removal of the typical contaminants and sampling process contaminants from the data set.

The bacterial group with the highest relative abundance remaining in the data set of the original subsurface communities was the Patescibacteria phylum, which are typical subsurface and groundwater-dwelling ultra-small bacteria. We also observed differences between the drillholes; for example, the Desulfobacterota phylum was present only in OTN2 at low relative abundance, whereas OTN3 hosted the Bdellovibrionota phylum.

P3.4

Temporal changes in terrestrial organic matter loading to coastal sediments of the Baltic Sea

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Early diagenesis in coastal marine sediments is primarily controlled by inputs of organic matter. These inputs may be derived from a range of autochthonous and allochthonous sources, which display variable reactivity in the sediment column and thus affect the balance between carbon burial and regeneration. In the low-salinity Baltic Sea, eutrophication and associated loading of autochthonous carbon have led to marked shoaling of sedimentary redox zones, promoting methane release and compromising the function of marine sediments as a carbon sink. However, up to 30% of organic matter in sediments of the Baltic Sea is estimated to be of allochthonous origin. Human activities in catchment areas, including forest clearance and ditching, may have significantly impacted fluxes of terrestrial organic matter across the land-sea interface, yet the scale of these impacts on carbon loading to marine sediments remains unknown. Here I will discuss new data from CuO extractions of dated sediment cores in the northern Baltic Sea, showing coherent temporal changes in the magnitude and composition of lignin inputs to sediments over the past five decades. These changes reflect the evolution of land use and forest industry activities during this period, suggesting a direct signal of changes in terrestrial organic matter inputs to marine sediments.

O4.1

Detect the unexpected – on the potential for unknown or undiscovered critical metal deposit types in the Fennoscandian Shield and its cover units

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Essentially traditional exploration for similarly traditional industrial and noble metals and their common host minerals has been at the core of the Swedish and, to a large extent, the overall Fennoscandian mining and exploration industry for a very long time. Yet, new times, new technologies, as well as societal demands, also require access to other, non-traditional metals and minerals – often sourced from faraway places and fraught with various ethical and/or strategic-geopolitical issues. This is something that we have become increasingly aware of since, at the very least, around 2009-2010 and the Chinese cut-down on rare earth element (REE) export quotas. This led, among other things, to the initiation of an EU classification of “critical raw materials” (CRM), successively updated and lately more forcibly promoted to the member states through the Critical Raw Materials Act (CRMA). The latter (again) pushed for the reduction of EU import-dependance for a majority of CRMs, while this together with the original crunch and later cut-downs also fueled a renewed interest in global REE and other CRM mineralisations, old as well as new, in the EU and in general, outside of China.

Despite these new demands, a majority of today’s relatively advanced CRM projects in the Nordic part of the Fennoscandian Shield and its cover units mostly encompass old discoveries and well-known deposit types, typically in familiar geological settings (*cf.* Jonsson et al. 2023, and references therein); so, what else could or should we be doing? During this talk I will highlight and exemplify this with some recent discoveries of previously unknown or thitherto unexpected CRM mineralisations and deposits from particularly the Swedish part of the shield and cover units, while also posing questions as to exploration issues and which other conceptual deposit types we could consider as possible future research and exploration targets. Besides the challenges associated with finding, among others, new carbonatites or Li-Cs-Ta-enriched granitic pegmatite systems in geologically old terrains with sparse exposure, which are the potential, probably unconventional CRM deposit types that we do not even realise that we should be looking for?

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O4.2

Metallogeny of Greenland and its critical raw material potential

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The transition to renewable energy systems requires substantial amounts of critical raw materials (CRMs). Greenland hosts extensive and geologically diverse terranes, recording more than 3.8 billion years of Earth history from the Archean to the present. This complex geological framework provides favourable conditions for the occurrence and potential development of mineral resources, including CRMs. This presentation examines the mineral potential for CRMs in Greenland within the context of its metallogenic evolution.

The richest concentration of CRMs in Greenland is found in the Mesoproterozoic Gardar rift-related alkaline province in South Greenland which is manifested by an exception accumulation of these resources. Most notable are the two intrusions Ilímaussaq and Motzfeldt containing some of the world's largest REE deposits but also host very significant Li, Be, F, Ta, Nb, Hf, U and Zr resources. REE deposits are also associated with carbonatites in West Greenland that also host P and Nb resources. East Greenland stands out by the very large Malmbjerg Mo deposit and the large PGM, Ti and V Skaergaard deposit, both related to Palaeogene intrusions, as well as the very large evaporitic Karstryggen strontium deposit. Additionally, and due to its relatively underexplored status, East Greenland can be considered to still hold a significant potential for yet undiscovered deposits of these commodities. Furthermore, this area also holds a significant potential for granite-related tungsten, tin, and antimony, as well as sedimentary copper mineralisation. The West Greenland Palaeogene Province is thought to hold a significant potential for conduit-type Ni-Cu-Co-PGM mineralisation. The Palaeoproterozoic terranes in West, South and East Greenland, have a potential for hosting undiscovered deposits of graphite, exemplified by the large Amitsoq deposit in South Greenland. The Thule black sands province, in North-West Greenland, holds a significant Ti endowment, illustrated by the Moriusaq and Thule deposits. Finally, the Palaeozoic Franklinian Basin of North Greenland has a very significant potential for Zn and Pb deposits, from which Ga and Ge can be possible by-products.

Quantified resources for many CRMs in Greenland are substantial, in some cases even significant on a global scale. However, it is important to recognize that most of the resource estimates for individual deposits are based on historical, non-compliant assessments. As a result, the estimated CRM tonnages come with considerable uncertainties and require further validation through resource evaluations that meet modern standards. Moreover, due to its relatively underexplored status, Greenland is likely to retain substantial potential for undiscovered deposits. Additional work is therefore needed to assess the island's CRM resources. While uncertainties remain, we conclude that the exploration potential for most CRMs is significant in Greenland.

O4.3

CRM in Norway - An overview

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Norway is host to many metals and minerals defined by the EU to be critical. Critical Raw materials (CRMs) include metals and minerals that are of high importance to the economy and with a high risk of disruption of supply.

Norway has a primary production of CRMs, but also a very important downstream production of critical metals, partly based on Norwegian mineral production. The potential for additional production of CRMs in Norway is considerable, and several resources are either under development or under investigation.

Norway is the most important producer of natural graphite and titanium minerals within Europe. The potential for additional resources of graphite is large and more than 25 occurrences are identified in Northern Norway. Several very large titanium deposits are identified in southern Norway. The Tellnes deposit in SW Norway is a world class producer of ilmenite that are refined to titanium oxide. In Western Norway titanium mainly is present in rutile hosted by eclogite, and recently, Nordic Mining AS started production of rutile and garnet from the 154 Mt Engebø resource at Sunnfjord.

The Fen carbonatite complex near Skien is identified as a world class potential resource for REE with 1.4-3.3 Gt of resources at 0.4-2% TREO. Neodymium and praseodymium, which are important constituents in permanent magnets, account for 15–25% of the REE found at Fen.

There are several resources of copper and other base metals under development and investigations, including the Nussir copper deposit in Finnmark, the Sulitjelma Cu-Zn ore district in Nordland and the Joma and Stekenjokk-Levi Cu-Zn deposits in Trøndelag and Västerbotten.

Potential phosphate resources are mainly related to igneous rocks, especially anorthosite-mangerite-charnockite-granite (AMCG) complexes, in which apatite is associated with high concentrations of Fe-Ti oxides. One of the major potential resources is situated in the Rogaland anorthosite province, where 1.5 Gt of resources are inferred. Another is the Kodal occurrence in Vestfold with an inferred and indicated 49 Mt resource with ca. 12% apatite which contains ca. 1% REO.

NGU collects data of metal and mineral occurrences and deposits all over Norway. The data compiled in NGUs resource databases, provides an important knowledge base for assessing the potential for CRMs in Norway. For the metallic registrations, NGU currently has a dataset of over 10,000 chemical analyses that include both major and trace metals (30-50 elements) from more than 2,000 registered occurrences. The analytical data can be used to define mineralisations and districts which are enriched in specific (e.g. critical) elements, indicating possibility of potential mining. Examples include cobalt, antimony, indium or bismuth enrichment in some districts of VMS deposits, cobalt enrichment in magmatic nickel deposits and vanadium in Fe-Ti oxide deposits.

O4.4

Rare Earth Mobilisation in Roof Zones of Alkaline Igneous Intrusions and the origin of Rheomorphic Fenite

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The roof zones of alkaline igneous intrusions often contain significant mineralisation in critical metals such as rare earths, tantalum or niobium. One such location is the Motzfeldt Region, Southern Greenland, which hosts what is considered to be one of the world's largest Ta deposits, as well as commercially significant amounts of Nb and REE. Glaciation has provided spectacular km-high vertical sections through the structure creating an extraordinary natural laboratory for the study of magmatic processes. In this system, a nepheline syenite magma ponded underneath sedimentary quartzite (the "Eriksfjord Group") forming a km-wide magma chamber. Interaction between the quartzite roof and the magma led to vertical gradients in silica content such that the top is quartz syenite grading down over ~300 m to nepheline syenite below. The interaction triggered the formation of Ta-rich pyrochlore in the roof zone. The magma was associated with an aggressive fluorine-rich fluid phase, which then modified the magmatic assemblage. The fluid mobilised REE and HFSE (but not Ta) from the pyrochlore. Rafts of quartzite, detached from the roof, were strongly hydrothermally altered ("fenitised") by this fluid, adding Na, Ca, REE and many HFSE elements scavenged from the pyrochlore. The replacement of quartz in the sediment by feldspar lowered the solidus temperature and the xenoliths partially melted to give a highly REE- and HFSE-enriched albite syenite melt. These melts penetrated the roof zone, forming a second phase of mineralisation in the system. The process by which country rocks are fenitised and then melted is a new genetic model. It explains the quite separate behaviour of REE and other HFSE in this system.

O4.5

Crustal-Scale Controls on Late-orogenic Cu-Au-Co Mineralization in Northern Norrbotten: Insights from a Mineral Systems Approach

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Northern Norrbotten, Sweden, is one of Europe's most prospective provinces for iron oxide–copper–gold (IOCG) mineralization, hosting Cu, Au, Co, Mo, U, and REEs within Paleoproterozoic supracrustal belts. Deposits formed where Fe-rich protoliths, long-lived tectono-magmatic activity, and crustal-scale shear zones converged, best understood through a mineral systems framework emphasizing energy and fluid sources, metal pre-enrichment, pathways, traps, and preservation.

Energy came from late-orogenic magmatism and metamorphism, generating oxidized, hypersaline brines. Metal sources were Fe-rich volcanic rocks, iron formations, and magnetite-bearing protoliths that acted as chemical sponges. Transport occurred along crustal-scale shear zones, active for >100 Myr and repeatedly channeling fluids, and forming a continuous IOCG belt (Bauer & Andersson 2023). This belt records extension at ~1.89 Ga and shortening at ~1.86 and 1.81 Ga, repeatedly reactivating conduits for mineralization (Bauer & Andersson 2023).

Traps include magnetite-rich protoliths, breccias, and dilation zones where fluid–rock interaction precipitated sulfides. Exploration footprints include sodic–calcic alteration grading into proximal K–Fe assemblages, amphibole–biotite–magnetite, and hematite enrichment. Geophysical proxies comprise magnetic and gravity anomalies and radiometric U–Th–K signals, while geochemical vectors such as Cu, Co, Au, La, and V anomalies in till and bedrock guide targeting.

Key deposits illustrate system processes. Nautanen records multiple pulses of oxidized brines forming chalcopyrite–pyrrhotite–magnetite ores (Bauer et al. 2022). Kiskamavaara hosts zoned Co- and Cu-rich lenses along subsidiary shears. Aitik exemplifies the porphyry–IOCG continuum, with early porphyry mineralization overprinted by IOCG assemblages. Collectively, these deposits highlight the importance of crustal-scale shear zones in localizing IOCG mineralization.

By integrating sources, pathways, traps, and preservation into a unified framework, the Exploration Information System (EIS) project delivers a predictive mineral systems model for Norrbotten. This highlights the province as a continuous IOCG belt of European significance and provides tools for reducing exploration risk and securing new raw materials essential for the energy transition.

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O4.6

Source and melting controls on LCT pegmatites in the Varuträsk area, Sweden

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LCT pegmatites form either by extreme granite fractionation (London 2018) or low-degree partial melting (Müller et al. 2017). These models can be tested by comparing pegmatite and granite ages, which should overlap if pegmatites are pluton-derived. Historic U-Pb TIMS ages from columbite (Romer & Wright 1992) and titanite (Weihed et al. 2002), and modern SIMS ages from zircon–monazite (Andersson et al. 2025) show S-type granites are 3–30 Ma older (including age uncertainties) than 1.78 Ga pegmatites, suggesting they were not the direct source. As part of the Horizon Europe project Exploration Information System (EIS: Grant n°1010557357), we present new lithogeochemistry data for metasedimentary rocks in Varuträsk and the broader region and compare their signatures with pegmatites and S-type granites to assess the role of partial melting in LCT pegmatite genesis.

Metasedimentary samples are metagreywacke and graphitic schist. On a $\Sigma\text{REE}+\text{Y}$ vs Zr plot, these rocks occupy an intermediate position between pegmatites and S-type granites, with the latter showing elevated $\Sigma\text{REE}+\text{Y}$ and Zr values. We infer the first melting event formed S-type granites at higher T, consuming REE-Zr phases and enriching the granites relative to source. Pegmatites are depleted in REE+Y and Zr, reflecting later low-degree melting that released Li from mica but left REE-Zr minerals in residue.

The combined age and geochemical data support a two-stage anatectic model in the Varuträsk area: (1) higher-degree partial melting of metasedimentary rocks at ca. 1.80 Ga forming S-type granites, followed by (2) a younger event at ca. 1.78 Ga generating pegmatitic melts directly from the source rocks. The Bothnian basin supracrustal rocks thus represent a common protolith, with the degree of partial melting, stability of accessory minerals, and amount of fractionation controlling the distinct signatures of granites and pegmatites. Although the role of 1.88–1.85 Ga intrusions is uncertain, we argue partial melting degree in metasediments and temperature were key to LCT pegmatite formation in this part of the Bothnian-Ostrobothnia basin.

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O4.7

Mineral chemistry in the Kaustinen lithium province – insights into the origin and evolution of pegmatite-forming melts

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The Paleoproterozoic albite-spodumene pegmatites of the Kaustinen lithium province (KLP) host one of the most significant estimated lithium resources in Europe. These Li-pegmatites have been studied for their economic potential and resource assessment for decades but, as for many other pegmatites in the world, the source of the pegmatite forming melts and the magmatic-hydrothermal processes behind the lithium enrichment are not fully understood. In this study, the major and trace element compositions of tourmaline, muscovite, albite and quartz from the albite-spodumene pegmatites and potential source granites in the KLP are analysed to investigate the origin and evolution of the pegmatite-forming melts.

In tourmaline and muscovite, compositional variation is observed on crystal to regional scale, revealing differences in melt sources, solidification vectors and the degrees of external contamination between individual albite-spodumene pegmatite swarms. Although albite-spodumene type pegmatites are generally simple in their textural zonation, the muscovite and tourmaline compositions show varying degrees of internal geochemical zonation, controlled by varying dominance between sidewall nucleation and simultaneous crystallization in the pegmatite dikes. Contamination from the wall rocks during the crystallization of the pegmatites is shown to affect mineral chemistry even in the inner zones of some pegmatites, evidenced by elevated concentrations of Mg, Ca, Ti and Sr in the rims of sharply zoned tourmaline crystals. Trace element (Rb, Cs, Sr and Ba) fractional crystallization modelling indicates that most of the region's pegmatites are not cogenetic with the Kaustinen pegmatite granite, which has been previously inferred as a likely melt source for the albite-spodumene pegmatites of the KLP. Our ongoing trace element studies of albite and quartz will yield further insight into the processes behind trace element variability in pegmatite-forming melts and will, for instance, constrain pegmatite crystallization temperatures in the KLP utilizing Ti-in-quartz thermometry.

O4.8

Spodumene formation by strong in situ fractionation of a lithium pegmatite in the Norwegian Caledonides

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The Scandinavian Caledonides are generally considered an orogeny with low lithium (Li) abundance, thus explaining the general absence of spodumene-mineralized pegmatites. However, in the Meløy-Glomfjord area of northern Norway several Caledonian Li-enriched pegmatites have been identified. The most evolved among these is the Ågskardet pegmatite, to date, the only known spodumene-bearing pegmatite in the Scandinavian Caledonides. The Ågskardet pegmatite was emplaced in the metasediments of the Caledonian Rödingsfjället nappe complex, immediately above the Caledonian basal thrust under high-grade amphibolite-facies conditions. The pegmatite exhibits complex mineralogical-chemical zoning, which is mapped as a wall zone at the contact with the host rocks, followed by intermediate and core zones. Spodumene crystals, ranging from 2 to 8 cm in size, are rare and restricted to randomly distributed quartz-rich domains within the core zone. Fine-grained albite zones occur discordantly across the intermediate and core zones, containing abundant colored tourmaline. To better understand the pegmatite-internal fractionation that caused the Li-enrichment and spodumene formation, major and trace elements of micas, feldspar, tourmaline, and quartz from the different zones were analyzed by EPMA and LA-ICP-MS. The results reveal a strong chemical zoning of the pegmatite body. Despite continuous Li enrichment in the remaining melt during progressing crystallization, spodumene formation did not take place until the final stage of pegmatite development. It is suggested that the crystallization of spodumene was suppressed due to the significant Li consumption by mica and tourmaline, whose crystallization was favoured by elevated levels of H₂O, F, and B. Bulk rock analyses of pegmatite zones and wall rocks indicate that the local Li enrichment of metasediments facilitated the formation of spodumene-bearing pegmatites in the otherwise Li-poor Scandinavian Caledonides.

O4.9

Integrating multiscale and multidisciplinary approach in the characterisation of Lithium-rich pegmatite for exploration and extraction

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Lithium plays a pivotal role in energy storage technologies, which are key to advancing the global transition to a sustainable, clean energy future. One of the few sources for lithium (Li) is highly fractionated pegmatitic granites, which are also enriched in caesium (Cs), tantalum (Ta), and occasionally rubidium (Rb) – known as LCT-pegmatites. Characterising pegmatite Li content through whole-rock geochemical analysis is a common first step in resource assessment, but it is insufficient on its own. The mineralogical hosts of Li must also be identified, as they determine the extractable resource. Measuring Li and its host minerals is notoriously difficult: its low atomic number challenges technologies designed primarily for detecting heavier elements. Furthermore, several rapid elemental Li-detection techniques such as Laser-Induced Breakdown Spectroscopy (LIBS) are relatively new and often lack sufficient standardisation, which can lead to spurious quantification results for unsuspecting users. Although time-intensive techniques such as X-ray diffractometry (XRD) can characterise mineralogy, they are limited in resolving low-level Li substitution in minerals like mica. While hyperspectral technologies are powerful for extrapolating microanalytical findings to satellite image scales, they face similar challenges in distinguishing Li-mica species and in detecting spodumene, the most extensively mined Li-bearing mineral.

Our aim is to develop multidisciplinary and multiscale workflows for well-standardised delineation of Li content and mineralogy in pegmatites for broader scientific and industrial use. In this contribution, we present recent case studies aimed towards developing approaches for lithium pegmatite characterisation with examples for potential applications in mineral exploration. The case studies include: 1) hyperspectral drill core and geochemical investigations of selected Australian LCT-pegmatites; 2) study of the Pilgangoora Li-pegmatite deposit (Pilbara, Western Australia), with analysis of a 1 km drill core hyperspectral dataset as well as related geoscience and microanalysis data; 3) study of Rb enrichment in Mt Edon Li-pegmatites (Western Australia); 4) investigation of a suite of Li-bearing pegmatites from Rajasthan, India, using a wide range of analytical techniques and extrapolation of key characteristics to satellite hyperspectral imagery; and, 5) hyperspectral exploration of Li-pegmatites in Angola using predictive modelling. We evaluate the strengths and limitations of the methods and workflows in each case study, highlighting the most effective tools and applications for rapidly and accurately determining Li content and characterising Li-bearing mineralogy, with the aim of advancing solutions beneficial to mineral exploration.

O4.10

Episodic thermal overprints in Bergslagen granitoids revealed by dual thermochronology: Implications for critical raw material systems

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The Bergslagen ore province, part of the Fennoscandian Shield, hosts world-class iron, base metal, and rare earth element deposits, underlining its importance for Europe's critical raw material supply. While often regarded as a stable craton, new evidence shows that far-field tectonic events repeatedly modified the crustal thermal structure, with direct implications for ore mobilization and preservation. Within the EU-funded *CRITTER* project, we apply dual thermochronology to granitoids surrounding key deposits (e.g., Bastnäs REE, Håkansboda Cu–Co) to uncover the thermal history for the past ~2 Ga. High-temperature Rb–Sr dating of biotite records mid-crustal cooling ages mostly clustering around 1.65 Ga, with variations between ~1700–1500 Ma and a possible westward youngening trend. A younger age of ~1430 Ma at Långban suggests localized reheating after Svecofennian orogenic cooling. Low-temperature zircon (U–Th)/He indicates no total reset at ~1.0 Ga and rules out large-scale Sveconorwegian overprinting. Instead, the broad age distribution points to protracted cooling and later Phanerozoic reheating, likely linked to Caledonian deformation and burial. These results demonstrate that episodic thermal events can affect even long-lived cratons, influencing mineral system preservation and reactivation. By integrating thermochronology with exploration geochemistry concepts, this work refines predictive criteria for identifying favorable conditions of ore remobilization in Fennoscandia's CRM provinces.

O4.11

A basalt fibre exploration model – a proposal

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Basalt fibers are used in a wide range of industries because of their weight savings, reliable mechanical properties and cost effectiveness.¹ Mafic volcanic rocks, especially basalt and basaltic andesite, are present in abundance in Iceland and, therefore, should be a bountiful basalt fibre resource. Also, since, in Iceland, the fibres will be produced by using 100 % renewable energy the expected reduction in production-associated CO₂ emission is ~30%. A country-wide search for a suitable mafic formation as a basalt fibre resource covering the available type and age range of petrographic and geochemical mafic lava types in Iceland showed that the massive, fine and even grained, basaltic andesite sequence of Flank Series of the Neogene 3.5-5.5 Ma Hafnarfjall-Skarðsheiði central volcano in West Iceland is by far the best suited mafic formations for basalt fibre production. This sequence of lavas belongs to the Brekkufjall Phase that is ~900-1000 m-thick and represents some of the earliest constructs of the central volcano. The Brekkufjall phase features, among other sequences, the mafic to felsic lavas and pyroclastic units of the “Brekkufjall Acid Series”, representing a brief eruption episode culminating in the formation of a caldera. It consists of two structurally distinct formations; i) The Brekkufjall Caldera Series (not considered further) and ii) The Flank Series, which flanks the Brekkufjall caldera and features the succession of interest. The Flank Series comprises a up to 700 m thick sequence of basaltic andesite, andesite and dacite lavas and is divided into two sequences. A ~300-400 m thick upper sequence consisting of rhyolite xenolith-bearing lavas that can be traced along strike for ~8 km and a lower one consisting of seven xenolith-free lava units with a collective maximum thickness of 300-400 m and thinning out northward over 1.5 km. It is this xenolith-free lower sequence lavas are well-suited for basalt fibre production, while the upper lava sequence is not because of the silicic enclaves. We put forward the hypothesis that the evolved (and crustal-contaminated) mafic lava sequences of the outer flanks of Neogene central volcanoes contain the ideal raw material for basalt fibre production and we will present our investigation of this concept as a viable exploration model for such a resource. Moreover, mafic magmatism in Iceland features a remarkably well-constrained geochemical source signatures, such as Nb/Y, Zr/Y and ¹⁴³Nd/¹⁴⁴Nd values, hence well suited as tracers for source identification of the raw material.

O4.12

Kupukka graphite deposit in Siikalatva, Finland – increasing European graphite resources

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The bedrock of the Kupukka area in Siikalatva, Finland represents mainly turbiditic sediments deposited on to the sea bottom as well as mafic pillow lavas (amphibolites) and possibly intermediate-mafic tuffs (hornblende gneisses). Graphite-rich layers occur often in the contact zone between sediments and mafic volcanics, which may indicate a quiet period in deposition of clastic sediments. Consequently, the Kupukka Graphite Deposit represents organic material originally deposited as sediment or mixed with sediment between 2.05 Ga - 1.96 Ga (DigiKP 2025). Also, geochemistry shows the close association of graphite-rich rocks with amphibolites and hornblende gneisses. During regional metamorphism and contact metamorphism around the pyroxene-rich granitoids and gabbros-diorites the organic material was crystallized as flake graphite. Based on the microscopic studies by Kupukan Grafiitti Oy the flake size is coarse, up to 1.5 mm. According to the preliminary Raman microscopy studies of drill core samples in Kupukka environment, the degree of crystallinity of graphite is very high, 96 – 98%. The crystallization temperature estimate for the studied samples was 682 – 683 ±50 °C, which corresponds to the metamorphic grade of the study area (high amphibolite-granulite facies, Kousa & Luukas 2007).

Two graphite ore types have been recognized, 1) high-grade breccia ore and 2) lower-grade disseminated ore. The host rock for the breccia ore has a breccia-type fabric, which may be connected to the closely associated Revonneva shear zone (Kousa & Luukas 2007).

Compared to the disseminated ore type the host rock for the breccia ore is massive and rich in clinoamphibole, which can be the dominating silicate in the rock, thus the rock is close to amphibolite in mineral composition. In addition to the clinoamphibole, plagioclase occurs as the main silicate mineral. Typical is also the abundance of titanite within minor minerals. The host rock for the disseminated ore is a graphite gneiss, which actually is a graphite-rich mica gneiss. The main silicate minerals are plagioclase, quartz and biotite.

Pyrrhotite is often abundant in both types of graphite ore. Pyrrhotite is magnetic, so graphite ore usually has a high magnetic susceptibility and can be traced by magnetic measurements. In places, especially in the upper parts of the mineralization and within shears, pyrrhotite has been altered to pyrite losing its magnetic properties. High remanent magnetism in pyrrhotite also modifies the magnetic anomalies.

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O4.13

Trace element and isotopic characteristics of Ga–Ge–In-bearing vein and breccia systems outboards of Caledonian erosional front

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Phanerozoic vein- and breccia-hosted Zn-Pb mineralisation in western Västerbotten forms a distinct mineral system which is superimposed on Palaeoproterozoic orogenic Au deposits of the Gold line and VMS deposits of the Skellefte district. Previous research on these deposits has focused on geochronological and fluid inclusion characteristics, whereas little data exist on sphalerite trace element chemistry. We present new LA-ICP-MS data from sphalerite in occurrences at Rävliiden, Nyliden, Lagbäcken and Svärträsk, supplemented with SF-ICP-MS, SEM, SIMS, EPMA, SEM-CL and EBSD analyses.

Sphalerite-bearing veins crosscut all ductile fabrics and are mineralogically distinct from the VMS deposits. A polyphase is suggested by evidence for repeated events of brecciation and cementation by sphalerite, galena, calcite, zeolite, fluorite and quartz. Sphalerite displays oscillatory zoning, twinning, and evidence for recrystallisation and overgrowth. EBSD reveals subtle crystallographic misorientation and twin boundaries, which correlate spatially with preferential enrichment of Ga, Ge, Sb, and Cu along growth zoning and twinning. Presence of Ga- and Ge-rich nano inclusions are suspected and will be investigated using atom probe tomography (APT)

LA-ICP-MS contents in sphalerite reach 385 ppm Ge, 196 ppm Ga, 2700 ppm Cd, and 66.3 ppm In, and are among the highest reported in sphalerite from Sweden. In contrast, sphalerite from nearby VMS exhibit significantly lower values, which do not exceed 0.49, 53.7, 1644 and 113 ppm respectively. A systematic west-to-east zonation is observed, with higher Ge and Ga concentrations in sphalerite from western localities (e.g. Svärträsk and Lagbäcken) than eastern localities (Rävliiden and Nyliden), coincident with an earlier identified T decrease from 150°C to 80°C based on available fluid inclusion data.

Stable ($\delta^{13}\text{C}$, $\delta^{18}\text{O}$, $\delta^{34}\text{S}$) and Pb isotope data indicate precipitation from low-temperature, connate fluids, possibly mixed with organic-bearing fluids. Pb isotopic compositions are distinctly more radiogenic ($^{207}/^{204}\text{Pb} \sim 16.2$) than Skellefte VMS ores ($^{207}/^{204}\text{Pb} \sim 15.1$), consistent with Phanerozoic leaching of Pb from Paleoproterozoic rocks during either the opening of the Iapetus Ocean, the Timanian orogeny, or both.

The results indicate previously overlooked exploration potential for Ga-, Ge-, and In-endowed Zn mineralization. The fine-scale heterogeneity in trace element distribution in sphalerite highlights the need for high-resolution analytical workflows to inform studies assessing primary ore as well as by-product potential and tailings revalorization.

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O4.14

Mineralization Paragenesis and Geochemical Constraints on the Rytkyнкylä Volcanic Sequence, Central Finland

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The Rytkyнкylä volcanic sequence (RVS), situated within the Raahe–Ladoga shear zone in central Finland, represents a likely 1.88 Ga volcanic rock unit of the Svecofennian orogen. This study integrates field observations, petrography, ore mineralogy, and whole-rock geochemistry, as well as the paragenesis of mineralization within the RVS. Field mapping and structural analysis reveal a lithological assemblage dominated by mafic volcanic rocks, with nearby granitoids exhibiting evidence of extensive brittle-ductile deformation and hydrothermal alteration. This is shown by a network of dextral faults and shear zones that have undergone deformation and metamorphism.

Petrographic and SEM–EDS analyses identified a diverse sulfide and oxide assemblage, including disseminated pyrrhotite, chalcopyrite, pyrite, arsenopyrite, marcasite, magnetite, ilmenite, and rutile. Textural and alteration characteristics reveal evidence for multiple hydrothermal pulses, including late-stage bismuthinite infilling fractures within arsenopyrite. Alteration assemblages are marked by pervasive silicification, potassium metasomatism, and epidotization across the lithologies. The hydrothermal origin of the deposit is further supported by geochemical indicators, as demonstrated by binary plots of the Ishikawa Alteration Index (AI) versus the Chlorite–Carbonate–Pyrite Index (CCPI). The indices yield values (CCPI: 59.54–97.73; AI: 32.73–47.25), delineating a well-defined zone of hydrothermal alteration.

Micro-XRF elemental mapping highlights strong geochemical associations among Fe–S, Co–Fe, and As–Bi, consistent with fluid–rock interaction during mineralization. Whole-rock geochemical data indicate calc-alkaline to tholeiitic affinities, characterized by predominantly peraluminous compositions and tectonic signatures consistent with volcanic arc and back-arc settings. Trace element analyses reveal gold concentrations up to 99 ppb, suggesting local mineralization potential. Collectively, these results constrain the magmatic and hydrothermal evolution of the RVS, indicating two to three stages of mineralization paragenesis. The presence of marcasite rims reflects late-stage hydrothermal activity at relatively low temperatures (~125 °C). The findings not only highlight prospective zones for mineral exploration within the RVS but also contribute to broader metallogenic models of Precambrian shear-related volcanic systems.

04.15

The hydrothermal Olserum-type REE mineralisations in the Västervik region, SE Sweden: new field evidence

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Recent exploration and mapping in the Västervik region of south-eastern Sweden have provided new insights into the formation of the hydrothermal rare earth element (REE) mineralisations of the “Olserum type”, recently linked to high-strain deformation zones (Tromp 2024). They are characterised by abundant fluorapatite and REE-phosphates hosted in veins dominated by biotite $\pm$ magnetite $\pm$ Fe-Mg amphiboles.

Based on new field observations gathered during a regional mapping project by the Geological Survey of Sweden, from both the Olserum–Djupedal area and newly discovered occurrences, several key features of the mineral system can be recognised. Mineralisation is spatially associated with large-scale NW–SE-striking deformation zones, but typically hosted by smaller, second-order structures with variable orientations, primarily E–W to NNW–SSE. The host rocks are alkali-feldspar-rich granites, typically displaying a pronounced foliation in mineralised areas.

North of the mineralised areas, variably deformed K-feldspar porphyritic to augen granites occur, likely belonging to the $\sim$ 1.85 Ga granite association. These rocks exhibit varying degrees of Na–Ca alteration, producing characteristic quartz-plagioclase assemblages. The contacts with the potentially younger host-rock granites are transitional, marked by a gradual loss of porphyritic or augen textures. The Na–Ca alteration has been proposed as a potential source of REE (Tromp 2024) but requires testing through geochronological studies.

The mineralised veins display mineralogical and chemical zoning both along strike and between different occurrences. While magnetite is a common component, REE-bearing veins found in newly discovered areas demonstrate that magnetite is not essential; most veins are dominated by biotite and fluorapatite $\pm$ REE-phosphates. In addition, the veins are not continuous along strike, suggesting “pinch-and-swell” structures from outcrop to regional scale. The veins are typically surrounded by cm- to dm-scale grey alteration haloes in the granite or by more intensely altered rocks comprising quartz $\pm$ biotite $\pm$ plagioclase; however, alteration is not invariably linked to the presence of REE-bearing veins.

The new results demonstrate that Olserum-type REE mineralisations form part of a structurally controlled, regional hydrothermal system. The Västervik region is therefore highly prospective and warrants further targeted research into the REE mineralising system and its potential links to other systems, including U-rich and Cu–(Co–Au–Mo–W) sulphide mineralisations, and the regionally developed Na–Ca alteration. The key field relationships and structural controls identified also provide valuable guidance for exploration and for targeting new REE-bearing areas in the region.

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O4.16

Hydrothermal alteration and its role in polymetallic mineralisation in the Riddarhyttan area, Bergslagen, Sweden

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Hydrothermal alteration halos are critical for understanding enrichment and mineralisation processes in hydrothermal ore deposits, yet in ancient, polymetamorphic terranes their relationship to mineralisation can be difficult to resolve. The Riddarhyttan area hosts one of the largest alteration halos in Bergslagen and contains diverse mineralisation, including stratiform Fe-oxide deposits, polymetallic sulphide ores (Cu–Co–Bi–Mo–Au), and the type localities of Bastnäs-type deposits, i.e. REE silicate-bearing magnetite skarns. All these styles occur within felsic metavolcanic rocks interlayered with sedimentary units and carbonates. Understanding the relationship between regional alteration and mineralisation is essential for reconstructing the ore-forming environment and for guiding exploration.

To investigate this, we integrated a large whole-rock geochemical dataset of rhyolites from drill core and historical analyses with multivariate statistics. Principal component analysis (PCA) and k-means clustering were used to classify alteration styles, validated through petrographic and mineralogical observations. This approach distinguishes weakly altered, K-altered, Mg-altered, and strongly Mg-OH-altered rocks despite extensive overprinting by metamorphism and deformation.

The classification enables detailed geochemical, textural, and spatial description of alteration styles. K-alteration, marked by Na depletion and K enrichment, is closely associated with stratiform Fe-oxide deposits, reflecting the upper levels of the hydrothermal system. Regional Mg-alteration, occurring both distal and proximal to ore, produced cordierite–mica–quartz schists depleted in Fe and LREE. Stronger Mg-OH alteration where cordierite is replaced by anthophyllite is linked to polymetallic sulphide zones and localised along shear zones and faults, showing structural control on later fluid circulation and base-metal deposition.

Together, these relationships define a multi-stage hydrothermal system. Early K-alteration accompanied stratiform Fe-oxide formation. A subsequent large-scale Mg-metasomatic event mobilised Fe and REEs from extensive volcanic rock volumes distal to the ore. Finally, structurally controlled Mg-OH alteration and sulphide deposition and remobilisation represent a later phase of fluid flow that overprinted earlier systems. This sequence provides a framework for understanding the spatial and temporal distribution of polymetallic mineralisation in Riddarhyttan. By integrating geochemical classification with geological context, this study demonstrates the genetic role of regional alteration in metal mobilisation and deposition. The Mg-alteration halo in Riddarhyttan likely served as a major metal source for ore-forming fluids. From both metallogenic and exploration perspectives, recognising such alteration systems is key to targeting REE and polymetallic resources in Bergslagen and analogous Proterozoic terranes worldwide.

O4.17

Magnetite trace element variation of the Blötberget iron oxide-apatite deposit in Bergslagen, Sweden

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The trace element and isotopic compositions of magnetite are commonly used as petrogenetic and thermometry indicators (Dupuis & Beaudoin 2011; Dare et al. 2014), although the effects of host rock composition, metamorphic recrystallisation and fluid/melt characteristics are understudied. Here we present trace element (TE) data of magnetite from the REE-bearing Blötberget iron oxide-apatite (IOA) deposit in western Bergslagen, Sweden. We report magnetite TE variability across the mineralised stratigraphy from 2 different ore bodies; Hugget and Kalv. The aim is to evaluate the degree of variability of TE content in magnetite relative to host rock composition and magnetite texture.

The Blötberget IOA deposit is hosted by a sequence of volcanic rocks that were metamorphosed up to amphibolite facies during the Svecofennian orogeny (1.87 – 1.80 Ga). The ore occurs as two moderately dipping lens-shaped bodies (Lindholm et al. 2014). The shallower body (Hugget) is banded and dominated by platy and aligned hematite with subordinate magnetite, whereas the deeper body (Kalv) consists of massive, granular magnetite. Intervals with iron mineralisation from drillholes BB-14-005 and BB-14-013 were systematically sampled. Magnetite grains were analysed by laser ablation inductively coupled plasma mass spectrometry at the University of Gothenburg.

The majority of the Blötberget magnetite has a high-temperature Kiruna-type TE composition. The magnetite TE contents vary significantly downhole, up to 3 orders of magnitude for some elements (e.g. Ti). Magnetite from the banded ore has lower TE contents and displays a stronger hydrothermal signature relative to massive ore magnetite. The data indicates that the TE composition of magnetite is highly variable within one deposit. Accordingly, future workers should refrain from using only a few magnetite samples to represent a larger deposit. Furthermore, our results imply that recrystallisation events can effectively alter the magnetite TE composition. Future work will focus on the effects of the host rock composition on the magnetite TE contents. The trace element data will be complemented by Fe- and O-isotope analyses on our magnetite samples, which is planned in the coming months.

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O4.18

Evidence for the association of evaporites with IOCG mineralization in the Peräpohja belt, northern Finland

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The Paleoproterozoic supracrustal belts of northern Finland host numerous polymetallic Au-rich deposits. Based on the current consensus, they mainly comprise atypical base metal-rich orogenic Au and IOCG deposits. The involvement of hyper-saline basinal fluids has been suggested as an important mechanism in formation of both deposit types. The presence of evaporitic strata in northern Finland has been speculated since the 1980s based on indirect evidence, such as widespread albitization, scapolitization and pseudomorphic textures. A turning point was the recognition of the belt-wide evaporitic Petäjäskoski formation (PFm) in the stratigraphy of the Peräpohja belt by Kyläkoski et al. (2012). Since then, anhydrite- and gypsum-containing rocks have been intersected by drilling at depth below the Rajapalot Au-Co deposit (Tapio et al. 2021). However, there is no direct evidence linking them to the PFm.

As part of the EU-funded REPower-CEST project we recognized a metasedimentary sequence resembling the PFm in the footwall of the Vähäjoki Fe-Cu-Co-Au deposit in southern Peräpohja belt. The sequence comprises metamorphosed carbonates, mudstones and sandstones. Ubiquitous disseminated hematite, a diagnostic feature of PFm, is present in all rock types and leads to red staining in carbonates and sandstones. Apatite is also widely present as fine dissemination, but locally forms distinct layers indicating a potential peritidal depositional environment. Importantly, fine anhydrite grains were found embedded in carbonate minerals giving support for an evaporitic origin. The chemistry of the mudstones from Vähäjoki fits perfectly with the phlogopite endmember of the PFm mudstones, having exceptionally high K₂O and MgO contents compared to other Karelian supracrustal rocks; high Ti, Ba, and Rb, and low Na and Sr concentrations also fit with PFm. The presence of barite veinlets rimming anhydrite-hosting carbonate, fine disseminated chalcopyrite, and REE-bearing phases indicate that the PFm rocks at Vähäjoki have been affected by hydrothermal processes that could produce high-salinity fluids needed to mobilize Fe, Cu and Co found in the Vähäjoki ore. This study offers the first direct evidence for the connection of evaporites to IOCG-style mineralization in northern Finland and highlights the importance of PFm as a fluid source for polymetallic mineralization in the Peräpohja belt.

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O4.19

Halogen systematics of metamorphic silicates associated with syn- and late-orogenic Si-Al-Ca metasomatism of ultramafic rocks, Outokumpu, Eastern Finland

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The Outokumpu ultramafic-hosted volcanic-associated massive sulfide Cu-Zn-Co-Ni deposit in E. Finland is of Paleoproterozoic age, polygenetic and affected by regional amphibolite-facies metamorphism, though genetic models remain elusive. Samples were retrieved from the Outokumpu Deep Drill Hole. Those investigated belong to the Outokumpu assemblage i.e., ultramafic rock (serpentinite and metasomatized ultramafic rock/metaperidotite), diopside and tremolite calc-silicate rock (referred to as skarn) and black schist.

Petrography, XRD and silicate EPMA are utilized in order to constrain the effect of devolatilization-derived metasomatic fluids during retrograde metamorphism. Halogens are used as trackers of this process. They may also provide insight into a potential component of synorogenic granite-related metasomatism.

Peak (M_3 , >550-670°C, 2-4 kbar) to early post-peak (static- M_3) stages are defined by antigorite-olivine-anthophyllite in the ultramafic rock. Residual olivine and early diopside and amphiboles have Cl/F mass ratios of 0.01-0.20. During retrograde evolution, amphiboles and, subsequently, talc and chlorite porphyroblasts (M_{4-5}) indicate a sulfide ore-related Si-Al-Ca-metasomatism in the ultramafic rock. Though amphiboles and talc show similar Cl/F ratios as before, chlorite shows ratios in the 0.03-3.00 range. The retrograde path resumes with serpentine replacing olivine and amphiboles and precipitation in veins in fibrous form. Serpentine is characterized by a trimodal distribution in a 0.02-15.6 range.

An increase in Cl/F ratios is observed as a function of mineral host and paragenetic stage during retrograde evolution. Low Cl/F ratios of M_3 silicates in metaperidotite and skarn indicate a potential influence from either devolatilized shale or granite-derived fluids. Amphibole and early retrograde antigorite are defined by higher F atoms per formula unit. The higher serpentine Cl/F ratios (M_{4-5}) are comparable with the minimum respective ratios of fluid inclusions from the same depth. This points to metamorphic brines generated during long-term water-rock interaction. The gradual influx of Cl, as recorded by metamorphic silicates, temporally correlates with the onset of the Si-Al-Ca metasomatism of the ultramafic rocks by silica- and carbonate-rich metamorphic fluids. Finally, the mobility of Ni, Co and other metals in this orogenic setting, that characterizes the Outokumpu deposit, might have been promoted by the Cl influx.

P4.1

Trace Element Geochemistry and U-Pb Geochronology of Scheelite and Cassiterite as Tools for Discriminating W-Sn Deposit Types in the East-Greenland Caledonides

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Efficient exploration in polyphase orogenic belts requires early tailoring to target deposit types and robust constraints on mineralization processes. In the East-Greenland Caledonides, scheelite and cassiterite occur in skarn, greisen, and quartz-scheelite vein systems. To resolve their formation history and geochemical signatures, twelve W-Sn occurrences between ~70° and 74°N were investigated using automated quantitative mineralogy (SEM), in-situ trace element analysis by LA-ICP-MS, and U-Pb geochronology of scheelite, cassiterite, and apatite. Combined petrographic, geochemical, and isotopic datasets were evaluated through multivariate statistics and compared with literature data to assess the potential of mineral chemistry as an exploration tool.

Mineralogical observations confirm that Knivbjerg, Gemmedal, Trekantsgletscher, Roslin, Kalkdal, and Milne Land represent skarn systems, Blokadedal, Berserkerbræ, and Canning Land correspond to greisen mineralization, and Margeries Dal, Panoramfjeld, and Galenadal host quartz-scheelite veins. Trace element compositions of scheelite and cassiterite from these outcrops vary systematically with deposit type, reflecting differences in fluid composition and geological setting. Multivariate analysis demonstrates that these variations allow for discrimination between skarn, greisen, and vein-related mineralization, providing a useful tool for exploration and provenance studies. U-Pb dating reveals three distinct mineralization pulses: ca. 425 Ma and 400 Ma, linked to magmatic-hydrothermal fluids from Silurian S-type and Devonian A-type granites respectively, and ca. 370 Ma, associated with metamorphic fluids during late-orogenic extension. No evidence exists for pre-Caledonian scheelite mineralization. The U-Pb lower intercept dates in scheelite overlap with the lower intercept dates from apatite most probably because they exhibit near closure temperatures, thus supporting its reliability for geochronology in mid- to low-temperature systems.

These investigations show that scheelite and cassiterite trace element geochemistry, integrated with petrographic and isotopic constraints, provide a valid and reliable tool for unraveling complex mineralization histories and can be used to optimize exploration strategies in orogenic terranes.

P4.2

The Co-Cu-(Bi-Ni) mineralisation at Los, central Sweden: a five-element vein-type deposit

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The Co-Cu-(Bi-Ni)-mineralised system at Los in Hälsingland, central Sweden, is a classic in both Swedish and international perspectives as it represents the first significant Swedish cobalt mine, and as the source of ore that led to the discovery of nickel by A. F. Cronstedt, published in 1751. Copper was first test-mined at Los, prior to the discovery of Co mineralisation there in the 1730s. The Los Co mines were in operation between 1737 and the late 1760s, and subsequently, attempts at re-opening them as well as exploration campaigns were mounted (e.g. Bergman et al. 2023 and references therein). Today, Co and Bi are classified as critical raw materials (CRM) in the EU (with “strategic” metals Ni and Cu), which has rekindled interest in this and other CRM-mineralised regions.

On-going work in the Los area by the Geological Survey of Sweden (SGU; cf. Bergman et al. 2023), has shown the vein-hosted mineralisation to be dominated by the sulpharsenides gersdorffite (NiAsS) and cobaltite (CoAsS). Variable amounts of bismuthinite (Bi₂S₃) occur isolated or associated with the previously mentioned minerals, while the originally mined Cu is mainly present as chalcopyrite. Notably, this mineral seems to mainly have formed prior to main-stage vein mineralisation. Uraninite occurs particularly in the immediate vein host rock (Welin 1966), while major non-ore vein minerals are calcite and quartz, with sparse barite and fluorite. The mineralisation occurs in a NW-SE-striking, steeply dipping calcite-dominated vein system hosted by relatively well-preserved Palaeoproterozoic metabasalt. Preliminary light stable isotope studies of the ore assemblages at Los show homogeneous positive $\delta^{18}\text{O}$ with moderately negative $\delta^{13}\text{C}$ for the vein calcite, and near-zero to modestly negative $\delta^{34}\text{S}$ for ore minerals. The character of the Los system is quite similar to so-called five-element vein deposits. Such deposits have a long history of mining, specifically in Central Europe. This deposit classification encompasses hydrothermal vein-hosted systems characterised by a combination of metals, typically Ni-Co-As-Ag-Bi in the form of arsenides/sulpharsenides, sulphides and native elements, often with uraninite and featuring calcite and quartz $\pm$ barite and fluorite as non-ore minerals (e.g., Kissin 1992). To conclude: despite the lack of silver in the system, a majority of observations suggest that the Los mineralisation represent a five-element vein deposit type, otherwise not known from the Swedish part of the Fennoscandian shield.

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P4.3

Two episodes of Proterozoic mafic magmatism and associated Fe-Ti(-V) mineralization in the Western Gneiss Region, Norway

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Fe-Ti(-V) mineralizations in Møre and Romsdal, Norway, are associated with metagabbro and amphibolite occurring as lenses in felsic gneisses in the Western Gneiss Region. The area is dominated by Palaeoproterozoic orthogneisses that have been deformed and metamorphosed during the Sveconorwegian and Caledonian orogenies.

The Fe-Ti(-V) mineralizations are spatially and genetically linked to mafic intrusions and can be classified as vanadiferous titanomagnetite deposits (VTM) formed by magmatic crystallization from melts originating from the same magmatic source as the host mafic rocks. The mineralized zones form discontinuous bands and lenses, which can extend over several 100 meters. They contain titanomagnetite, which is variably vanadium-rich, and ilmenite. Original shapes and textures have been largely obliterated by deformation, particularly during Caledonian continental subduction and HP metamorphism and subsequent late-Caledonian extension associated with intense WSW-ENE stretching and strike-slip shearing in high-strain zones.

U-Pb zircon LA ICPMS dating reveals that the dioritic to granitic orthogneisses formed around 1695–1660 Ma, which is consistent with previous dating in the area. Their geochemical signatures indicate that they formed in a subduction zone setting and intruded into a magmatic arc. Gabbro bodies north of Langfjorden (Raudsand–Skåla) hosting Fe-Ti(-V) mineralizations formed at ca. 1660 – 1650 Ma, i.e. at roughly the same time as the surrounding orthogneisses, suggesting a common origin. This is supported by their geochemistry, which is consistent with a magmatic arc environment. The biggest deposit in the area (Raudsand) belongs to this group. A new finding is the identification of a second, separate event of gabbro intrusion, some of which is also associated with Fe-Ti(-V) mineralizations. The dated metagabbros to the south of Langfjorden are between approximately 1470 and 1460 million years old - almost 200 million years younger than the mafic intrusions in the Raudsand area. Like the older generation, they formed in a subduction zone setting but were emplaced at a greater distance to the magmatic arc, probably in a back-arc basin. The ores associated with the metagabbros of these two age groups share many characteristics, but differ in their titanium content, which is significantly higher in the younger population.

The study thus identified two key periods of gabbro intrusion and coupled Fe-Ti(-V) mineralization: around 1650-1660 Ma and 1460-1470 Ma. These periods were both associated with episodes of subduction and magmatic arc development along the active western continental margin of Fennoscandia. The identification of two episodes of mineralization linked to two age groups of gabbro intrusions also expands the search pattern for further Fe-Ti-V deposits, as it now includes younger mafic intrusions aged 1460–1470 Ma.

P4.4

Rare-earth element evolution of the Sokli carbonatite complex: new insights from drill core observations, geochemistry, and mineralogy

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Rare-earth elements (REEs) are critical metals for the green energy transition, as they are used in many low-carbon technologies. Globally, most REEs are sourced from carbonatite deposits; however, production is focused on a handful of deposits, creating a serious supply risk. The Sokli carbonatite complex in northeastern Finland is one of the largest carbonatites in the world and the presence of REE mineralisation in Sokli has been reported, however comprehensive studies have not been conducted.

The preliminary objectives of the study are to define the mineral and chemical composition of the REE-enriched rock types in Sokli, reconstruct the primary mineralogical composition, and evaluate the 3D-distribution of the mineralisation. Isotope studies are also of paramount importance to improve the understanding of the magmatic-carbohydrothermal evolution and the sources of the magmas.

Detailed geological observations from new drill cores have revealed intricate cross-cutting relationships between REE-enriched carbonatite within the Sokli central fracture zone. Multi-phase alterations have created complex mineral assemblages: common carbonates are found together with uncommon REE-fluorocarbonates, such as kukharenkoite and cordylite, as well as with many different oxide, phosphate, silicate, and sulphide phases.

The recent drill core observations accompanied by geochemical and mineralogical studies have allowed more detailed descriptions and division of the last main magmatic-carbohydrothermal stage (stage 5 of Vartiainen 1980, 2007) in the Sokli paragenesis. Various isotope systems, such as O, C, S, Sm-Nd, Rb-Sr, and B, will be used to constrain the magma and fluid sources for this stage, as well as the broader paragenesis of the Sokli carbonatite complex. The results have wide-reaching implications for future exploration and mineral processing. The availability of material from drill cores with a proven 3D context means that the Sokli carbonatite complex can become a key case study in carbonatite petrogenesis globally.

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P4.5

Zircon U-Pb, Hf and trace element systematics in melteigite and calcite carbonatites, Fen alkaline and carbonatite complex, Telemark, southern Norway

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Carbonatites are the primary source of Nb and REE in the world and an important source of phosphorous in Europe. The processes behind the evolution of alkaline and carbonatite melts, leading to economical concentrations of critical elements are debated.

The Fen alkaline and carbonatite complex is a 2 km-diameter pipe-like intrusion, emplaced in Mesoproterozoic Sveconorwegian gneisses. Lithologies range from pyroxenite and melteigite in the west to carbonatite which becomes increasingly Fe-rich towards the east. Fen was formerly mined for Fe and Nb and hosts the largest REE deposit in Europe known to date.

This study presents new in-situ U-Pb and Lu-Hf isotope and trace element data acquired on zircon from ultramafic rocks and calcite carbonatite samples from a 70m-long core from the central part of the complex. Zircon, while considered one of the most robust minerals, can be challenging to date in carbonatite systems where U is scarce. Nonetheless, the mineral incorporates High Field Strength Elements such as Nb and therefore can be used to monitor the evolution of the melt/fluid throughout its crystallization.

Cathodoluminescence imaging reveals several generations of zircon where cores display evidence for recrystallization, while rims are bright and weakly oscillatory zoned. U-Pb geochronology by Laser Ablation Multi Collector Inductively Coupled Mass Spectrometry indicates that U-Pb systematics are dominated by either recent Pb loss or by non-radiogenic Pb where U concentrations are low. Despite these challenges, we obtained six Concordia ages ranging between 576 and 583 Ma.

The median ϵHf_{580} value is 1.9 ($n=54$) with an associated depleted-mantle model age (TDM) of 1380 Ma and indicates non-negligible crustal contributions, a feature not seen in in-situ Nd isotope data obtained on REE fluorocarbonates in the Fe-dolomite carbonatite (median $\epsilon\text{Nd}_{580} = 6.6$, TDM = 650 Ma; Liu et al. 2024). The discrepancy is either due to variable extent of crustal interaction in the complex or to buffering of Nd isotopes in a system where REE derive from the mantle.

Niobium, Sr, Th and U correlate inversely with Ti in zircon. A stronger depletion in U compared to Th results in unusually high Th/U ratios (>100 to 100000), consistent with fractionation of pyrochlore and apatite and the transition towards a carbonatitic system.

Despite challenges related to the complex history of carbonatite, zircon in Fen crystallized over a protracted range of temperatures, thus recording the chemical evolution of the system and shedding new insights on the role of crustal interaction in alkaline and carbonatite complexes.

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P4.6

Mineralogy and ore textures of Nb-Zr-REE-rich lava flows from Sæteråsen, SE Norway.

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The Sæteråsen Nb-Zr-REE-mineralization is confined to two 500-700 x 50 m lense-shaped bodies of aphyric trachytes within a stack of porphyritic trachytes and rhomb porphyries associated with the Permian Oslo Rift. Whole rock data from surface samples and drill cores (Ihlen 1983) show consistent grades of ca. 1-1.5 wt% Zr, 2000-2500 µg/g Nb, and 3500-4000 µg/g Σ REE+Y throughout the mineralized bodies. The minerals hosting Zr, Nb and REE are zircon, chevkinite, pyrochlore, euxenite-Y, minor zirconolite, and possibly gadolinite. In addition, titanite may have up to 5 wt% Nb. Zircon is unevenly disseminated throughout the matrix, typically as < 10 µm inclusions in all major minerals. Chevkinite may occur as 5-50 µm matrix minerals, in clusters with Mn-rich magnetite, up to 200 µm subhedral grains grown interstitially in clinopyroxene veinlets, or overgrowths and replacement products of REE-rich apatite rims. The La and Ce contents in chevkinite vary strongly, showing a bimodal distribution. Pyrochlore form 5-50 µm sub-euhedral crystals in the matrix or smaller inclusions in most major and minor minerals. Spotty zonation is common. The main host of HREE and Y is euxenite-Y, with 5-12 wt% Σ HREE and 15-20 wt% Y. Although less common, euxenite-Y is typically associated with other REE- and Nb-bearing minerals. Remobilization of REE is evident from submicron veins of monazite cutting the primary minerals, and coating along grain boundaries. Monazite also occasionally replaces the high-REE rims of primary apatite.

Macroscopic textural variation in the ore body is due to variable occurrences of clinopyroxene (aegirine-augite) and Fe-oxides, which may be disseminated in the feldspathic matrix, form interstitial fine-grained aggregates enclosing globules of fine-grained matrix minerals, coarser-grained angular clusters interstitial to the matrix, veinlets, or patches. Contacts between globular, laminar, patchy and aphyric textures are sharp, and may vary down to thin section scale. The chemical composition, Mn in particular, of the gangue minerals vary from sample to sample, but a correlation between mineral chemistry and texture is not exclusive. This indicates that the textural and chemical variation may be a result of both multiple pulses and local heterogeneity within the lava flows.

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P4.7

Rapid ore mineral identification and Li₂O estimation in Bergby LCT-pegmatites with the Orexplore GeoCore X10

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The Bergby LCT-pegmatite field in the Ljusdal Lithotectonic Unit is one of the most promising lithium projects in Sweden. Covering c. 80 km², it was first identified in 2007 and further delineated by exploration and drilling campaigns. It consists of at least ten LCT pegmatite dykes or dyke swarms. The main Li-ore are spodumene and petalite, together with fine-grained spodumene–quartz intergrowth (SQUI) (Leijd et al. 2023). These phases are often difficult to distinguish from common pegmatite gangue minerals in drill cores, complicating logging and ore characterization.

To address this, two drill cores were analysed with the Orexplore GeoCore X10 scanner, which simultaneously collects X-ray computed tomography (XCT), X-ray fluorescence (XRF), and density data (Bergqvist et al. 2019). Distinct XCT attenuation intervals were defined for spodumene, petalite, quartz, feldspar, muscovite and other accessory phases. These were later compared to Raman spectrometry and powder X-ray diffraction (XRD) to validate the mineral identifications.

Results show that petalite–spodumene ratios can be calculated directly from the XCT volumes, allowing for customization of the mineral processing procedures (e.g., Yelatontsev & Mukhachev 2021). Comparisons with assay data demonstrate strong correlation, though XCT-based concentrations are systematically lower, largely due to lithium hosted in gangue minerals, such as muscovite, tourmalines and phosphates. Limitations are related to the partial overlap of attenuation intervals (e.g. spodumene vs. k-feldspar) and the 200 µm voxel size, which may underestimate the contribution of fine-grained textures.

These results demonstrate that the Orexplore GeoCore X10 is a powerful tool for rapid, non-destructive characterization of pegmatite-hosted lithium ores. Beyond routine identification, it provides volumetric mineral quantification, textural information, and reliable Li₂O estimates. This method thus offers significant potential for exploration, resource evaluation, and processing optimization.

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P4.8

Critical Metal Deportment in Polymetallic Ores: Advancing the Understanding of Cobalt in the Zinkgruvan Deposit, Bergslagen District, Sweden.

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Cobalt (Co) is a critical metal, and its importance in the green transition has triggered an interest in understanding its deportment in polymetallic deposits. In these deposits, Co may occur as a trace element in sulfides (e.g., sphalerite, pyrrhotite, chalcopyrite), influencing flotation and reagent regime during the Zn–Pb flotation process (Babedi et al. 2021), and decreasing the value of Zn concentrate. At the same time, Safflorite (CoAs₂) offers potential to recover Co as a by-product while reducing arsenic in tailings, lowering environmental impact. A multi-method approach to characterize Co-bearing minerals in polymetallic ores is necessary to predict processing performance. This study builds on the initial assessment of Co occurrence in the Zinkgruvan deposit and aims to expand mineralogical and geometallurgical understanding across spatial and lithological domains.

The Zn–Pb–Cu–Ag Zinkgruvan deposit in southern Sweden comprises diverse ore bodies with variable mineralogical associations and characteristics. Two main mineralization styles have been defined: stratiform Zn–Pb–Ag ore hosted in quartz- and calc-silicate-rich metatuffite, and dolomite marble- and skarn-hosted Cu–Zn ore (Jansson et al. 2017). The complexity and polymetallic nature of the ores increase towards the western part of the deposit, where available geochemical and mineral chemical data outline a trend of increasing Co, Ni, As, and Sb. Hjorth (2022) showed that Co in Zinkgruvan occurs as free minerals (cobaltite, safflorite, cobalt pentlandite) and within the lattice of pyrrhotite and sphalerite, based on samples from the Dalby–Mellanby ore body in the westernmost part of the deposit. Detailed core logging of this area shows small amounts of Co minerals. Cobalt-rich core intervals, according to chemical assays, coincide with sphalerite and pyrrhotite occurrence, yet no Co minerals are observed.

Based on this initial assessment of Co presence in Zinkgruvan, further steps will include mineralogical characterization of Co-bearing minerals across spatial and lithological domains, as well as evaluating Co deportment variability among ore types.

Acknowledgments

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P4.9

Characterizing flake graphite using traditional and advanced tools: Insights from Australia's Leliyn Flake Graphite deposit, Northern Territory

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Flake graphite is a critical mineral for energy-transition technologies, but many geological provinces worldwide remain underexplored. Within Australia's Paleoproterozoic Pine Creek Orogen, the contact-metamorphic Leliyn deposit represents one of the country's largest flake graphite resources—and a giant deposit by global standards—currently in its early development phase. Here, we present results from a comprehensive multi-scale characterization of its graphitic schists, employing traditional petrography in combination with advanced mineralogical and spectroscopic approaches to determine key ore parameters, including flake size and graphite crystallinity, across the deposit (cf. Baumgartner & Pejic 2025).

Our integrated workflow—combining optical and electron microscopy, SEM-based automated mineral mapping, X-ray diffraction, FTIR spectroscopy, and both bulk and grain-scale Raman spectroscopy—shows that the mineralization originated from organic-rich sedimentary precursors. An initial greenschist-facies regional metamorphic event imparted schistosity, followed by high-temperature contact metamorphism (≥ 600 °C) associated with nearby magmatic intrusions, which promoted graphitization and the development of groundmass alkali feldspar and andalusite porphyroblasts. Subsequent hydrothermal overprinting imparted phyllic alteration and partial recrystallization.

The resource is dominated by fine-flake graphite (<100 μm), with locally coarser flakes (>100 μm) in less schistose, feldspar-rich domains. Structural order determined by XRD is generally high ($d_{002} \sim 3.357$ Å; $L_c \sim 800\text{--}1300$ Å). Confocal Raman spectroscopy revealed within-ore and intra-flake variability in crystallite size and disorder introduced by late-stage hydrothermal alteration. While this fine-scale variability prevented the determination of representative ore-scale parameters, cost- and time-efficient bulk Raman spectroscopy yielded robust deposit-scale averages unattainable through conventional confocal analyses. It further demonstrated that, at the bulk scale, the original high crystallinity from contact metamorphism was largely preserved despite localized alteration effects.

Collectively, these findings demonstrate the value of integrating traditional petrography with advanced mineralogical and spectroscopic methods for unravelling deposit formation histories and constraining graphite characteristics relevant to early-stage processing performance and downstream potential. More broadly, this workflow offers a transferable framework for characterizing flake graphite deposits in metamorphic terrains worldwide, and emphasizes the importance of tailored deposit-scale assessment for ensuring future critical mineral supply.

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P4.10

Using tourmaline as a petrogenetic indicator and vectoring tool for Li pegmatites: a case study from the Somero-Tammela Li province, Southern Finland

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The increasing demand for lithium (Li) shows no unwinding in the future as it has become a major raw material solution for sustainable development, especially in the electronic transportation industry. The Somero-Tammela area is one of the major Li pegmatite provinces in Finland, hosting significant Li mineralization. In this study, tourmaline chemistry, coupled with detailed field mapping, is used to investigate the petrogenetic processes behind the formation of (Li) pegmatites and to assess the potential of tourmaline chemistry as a vectoring tool for Li mineralization. The Somero-Tammela area covers over 200 pegmatite dykes with well-preserved outcrops, making it ideal for regional-scale pegmatite studies.

Most pegmatites in the Somero-Tammela area can be divided into four distinct types according to their mineralogical composition: 1) albite-petalite pegmatites ($\pm$ spodumene as a petalite alteration product), 2) K-feldspar-petalite pegmatite with significant Cs (pollucite), 3) beryl-bearing quartz-K-feldspar pegmatites, and 4) common quartz-K-feldspar pegmatites. The pegmatites are hosted by metamorphosed supracrustal (mafic metavolcanics and metasediments) rocks, represented by schists, amphibolites, gneisses, and granodiorites. Mineralogical zonation is observed at various scales. The Kietyönmäki albite-petalite/spodumene pegmatite swarm, which hosts the most significant Li mineralization in the region, shows mineralogical variation between individual pegmatites, whereas the Cs enriched pollucite bearing Luolamäki K-feldspar-petalite pegmatite has a particularly developed internal zonation.

Tourmaline is commonly found in all pegmatite types. They mostly occur as disseminated throughout pegmatites, except in zoned pegmatites, where they may be concentrated in mineralogically distinct zones. Most tourmalines are black and represent Mg-Fe solid solution (i.e., dravite-schorl) tourmalines. The major and trace element compositions of tourmalines is analyzed from the core and contact zones of individual pegmatites, as well as from mineralogically distinct pegmatite types associated with different country rocks. We use the results to model the fractionation processes involved in pegmatite formation, constrain their potential source(s), and assess the fluid-rock interaction of pegmatites with host lithologies. In addition, by comparing the tourmaline chemistry of Li-mineralized and barren pegmatites, we aim to test its potential as a vectoring tool for Li mineralization.

P4.11

LA-ICP-MS imaging and semi-quantification: Unlocking REE potential of low-grade sedimentary ores, application to Estonian Phosphorites under REMHub project

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REEs are used in a wide range of high technologies. Current sourcing is derived from igneous deposits, a production incompatible with the substantial demand for specific REEs (Nd, Pr, Dy). This, along with the scarcity of resources, has spurred interest in waste valorisation and unconventional ores (Hoshino 2016). Alternative raw sources of REE include numerous low-grade and high-tonnage formations, polymetallic nodules, black shales, and sedimentary phosphorites. The characterisation and extraction of valuable metals from these are challenges due to deposit complexities and the state of knowledge. The latter is particularly important in the case of phosphorites, which have been highlighted as potential REE sources. However, REE contents are often below the detection limits of FE-SEM automated mineralogy techniques, thus problematic for recovery planning.

This study focuses on Estonian phosphorites, which constitute Europe's largest phosphate rock reserves and are characterised by apatite shell fragments (Graul 2023). In the REMHub project, investigations were conducted on three deposits: Toolse, Aseri, and Ülgase; representing a dataset of 600 ablations up to date. The LA-ICP-MS imaging technique developed by Drost (2018) addressed REE distribution determination and apatite enrichment, allowing identification and discrimination by integrating semi-quantitative data through elements' stepwise distribution. Diagenetic stages and compositions were evaluated using the following pathfinders as pooling channels: Sr, U, and Ce.

Apatites present homogenous REE patterns, MREE-enriched up to 15-fold compared to PAAS, with Y-Ce anomalies indicative of early-diagenetic overprinting. However, the extent of overprint varied. In Toolse, shells show less recrystallised textures, with Sr-U-depleted stages allowing the tracing of pristine signals. Average REE grade is 1966ppm. In Aseri, U-sorting reveals a second, alteration-driven enrichment in which the fragment edges present a Σ REE up to 12754ppm. Ülgase presents a second type of apatite of pure authigenic origin, and lesser enrichment (400-800ppm) compared to shells (1500-3000 ppm).

Despite enrichment magnitude differences, deposits' distributions are similar: main REEs are Ce(33%), Y(21%), La(12%), Nd(16%) and Dy(3%). On average, U concentrations are approximately 90ppm in Aseri and Toolse, 40ppm in Ülgase; and toxic elements (Cd-Zn-Th) are found in traces.

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P4.12

Critical metals behavior in amphibolite facies: metamorphic conditions and ore mineral compositions Sulitjelma and Bleikvassli Pb-Zn-Cu mines, Norwegian Caledonides

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As part of the Critical Metals in Orogen project (<https://anr-cmio.gm.umontpellier.fr/>), this study focuses on the presence and potential remobilization of critical metals, especially Indium, at the historic Sulitjelma Cu-Zn and Bleikvassli Zn-Pb-Cu mines in the Norwegian Caledonides. The style of mineralization is considered VMS and SEDEX, respectively, but both localities have suffered metamorphism and deformation during the formation of the Caledonian orogen.

Ore and host rocks samples of the Sulitjelma and Bleikvassli mines were studied in order to understand the link between metamorphism, mobility, and critical metal concentrations within the mineralizations. To address this issue, several methods were used: macroscopic and microscopic analyses, thermodynamic modelling, EBSD, LA-ICP-MS, LIBS and EPMA *in situ* analysis. The host rocks are mostly metasediments composed of quartz, micas, garnet, staurolite, kyanite and rare sillimanite. Using pressure-temperature diagrams calculated for the host rock, we obtain for Bleikvassli, temperature conditions between 650 and 750 °C and pressure conditions between 6.5 and 11 kbar. For Sulitjelma, the metamorphic conditions are slightly lower, with temperatures between 550 and 700 °C and pressures between 5 and 12 kbar. These data suggest that the host rocks of the Bleikvassli and Sulitjelma mineralizations experienced amphibolite facies conditions associated with Barrovian metamorphism in a collisional context, in agreement with the available literature.

Ore samples are dominated by pyrite–chalcopyrite–sphalerite and pyrrhotite–chalcopyrite–sphalerite assemblages, with the local presence of magnetite. EBSD results show that, in most of the samples, pyrrhotite, pyrite and chalcopyrite show a preferential orientation possibly indicating dynamic recrystallization whereas, sphalerite, appearing texturally late might have crystallized under static conditions. EMPA and LA-ICPMS *in situ* analytical results on the mineralizations indicate the presence of significant iron in sphalerite in both deposits with 4.4 wt% at Bleikvassli and 5.7 wt% ppm at Sulitjelma. In addition, cadmium, manganese, and indium are preferentially incorporated into sphalerite as well. In both deposits, there is a significant amount of indium in sphalerite, up to 55 ppm. Gallium and germanium concentrations in sphalerite are low. Indium and manganese are also present in chalcopyrite but at lower concentrations. By contrast, tin and silver are preferentially incorporated into chalcopyrite. Cobalt, nickel, and arsenic are enriched in pyrite.

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P4.13

Thermodynamic modeling of LREE-enrichment in alkaline magmas: effects of fractional crystallization, assimilation, magmatic H₂O, and pressure

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Alkaline silicate rocks host significant rare earth element (REE) resources on Earth (Batapola et al. 2020). Enrichment of REEs in them has been linked to fertile sources, high degree of magmatic differentiation, hydrothermal events, and/or weathering (Beard et al. 2023; Chakhmouradian & Zaitsev 2012). The roles of fractional crystallization, crustal assimilation, magmatic H₂O, and pressure during differentiation on REE enrichment remain unclear. As our case study, we used a thermodynamically constrained modeling software, Magma Chamber Simulator, to study the effects of these factors on light REE (LREE, such as La and Ce) enrichment in Mesozoic Weishan alkaline complex, which hosts the third largest known REE deposit in China.

Our simulations show that higher H₂O and pressure values (parental melt H₂O: 0-3 wt%, wall-rock H₂O: 0-1.5 wt%, pressure: 150-380 MPa) promote LREE enrichment in the residual melt. In the FC process, the crystallization of LREE-poor anhydrous minerals increases both LREE and H₂O contents in the residual melt. The progressively increasing H₂O promotes LREE-enrichment in the residual melt, while decreasing pressure suppresses it due to effects of these factors to mineral assemblages and crystallization temperature. At a high degree of FC (90%), LREE content in the residual melt is ~4 times that of the parental melt. Importantly, assimilation of low-LREE wall-rock melt dilutes magma LREE content, lowers magma temperature and H₂O content, and modifies mineral assemblages, collectively inhibiting LREE enrichment in the residual melt. Therefore, high degree of assimilation suppresses LREE-enrichment in the magma. Our model offers new insights into the role of alkaline magma differentiation and related LREE enrichment globally.

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P4.14

Characterization of platinum-group elements-bearing minerals (PGM) and associated phases of the Karasjok Greenstone Belt (KGB), Arctic Norway

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Determining and quantifying the mineralogy and mineral associations of platinum-group elements (PGE)-bearing minerals is challenging due to their commonly small grain size. However, an understanding of the associated sulfide and silicate phases is crucial for an assessment of the recoverability, and hence, economic value, of these target minerals. Such textural relationships also help with a better understanding of the processes affecting the distribution of PGEs in magmatic sulfide deposits (Howell et al. 2017). The Paleoproterozoic (2.45 – 1.95 Ga) amphibolite-facies volcano-sedimentary units of the Karasjok Greenstone Belt (KGB), Arctic Norway, contain Ni-Cu-PGE-mineralized (ultra)mafic intrusions, such as the Gállujavri (2051 ± 8 Ma, U-Pb zircon age) and the Porsvann metapyroxenites and metagabbros (2056 ± 10 Ma, U-Pb zircon age; Hansen et al. 2023; Orvik et al. 2022).

Bulk mineralogy and sulfide assemblages were investigated using automated mineralogy. For this study, bulk mineralogy was acquired using line scan and a phase of interest (POI) search for PGMS due to their commonly small grain sizes. Preliminary results of the ongoing analysis indicate that the PGMs are predominantly hosted within silicates and at the silicate-sulfide grain boundaries, but also occur as inclusion in sulfides. Furthermore, gold in the form of electrum is found in noticeable quantities. The mineral scans targeting sulfide minerals, revealed that the Ni-rich millerite is a major sulfide phase, together with pentlandite, chalcopyrite, pyrrhotite, pyrite, and minor cubanite.

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P4.15

Mineralogy and textures of REE–Y–U/Th–Ti/Nb–Fe-bearing assemblages from different critical mineral occurrences in the Västervik region, SE Sweden

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The Västervik region of south-eastern Sweden hosts a diverse range of mineralisations, including Cu–(Co–Mo–Au–W) sulphide and iron oxide deposits, and several rare earth element (REE) and U occurrences. Beyond the well-documented Olserum–Djupedal REE phosphate mineralisation, many hydrothermal REE–U mineralisations remain poorly characterised despite increasing exploration interest in the region. This study presents new mineralogical and textural data for some lesser-known occurrences, obtained as part of a regional mapping project by the Geological Survey of Sweden aimed at improving the understanding of the critical mineral systems in the region.

The Trostad, Björkö and Melsjön occurrences feature broadly similar REE–Y–U/Th–Ti/Nb–Fe-bearing assemblages. At Trostad, mineralisation occurs in syenite replacement veins in gabbro, associated with biotite-magnetite-ilmenite. At Björkö, mineralisation forms fissure fillings associated with ilmenite-rutile in plagioclase-dominated rocks related to Na–Ca alteration (Hoeve 1974). Back-scattered electron imaging and semi-quantitative SEM-EDS analyses show that crichtonite-group minerals are closely associated with the Fe–Ti oxides. The crichtonite-group minerals exhibit variable compositions and alteration, typically Y–U±Zr-bearing but lacking detectable LREE. Coarser-grained REE-bearing epidote or allanite-(Ce) and subordinate Y–U–Ti-rich euxenite/aeschynite-group phases, uraninite, a Ce–Y–Ti-rich chevkinite-group mineral, thorite, xenotime-(Y), zircon or fluorapatite appear as seemingly primary minerals associated with the main Fe–Ti minerals. Bastnäsite-(Ce)/(La) mainly forms from the alteration of allanite-group minerals or other REE phases. At Björkö, a LREE–Pb-rich mineral, probably gysinite-(Ce), is also linked to late-stage alteration. The Melsjön mineralisation is comparatively simple, dominated by a crichtonite-group mineral and bastnäsite-(La) with titanite, rutile and ilmenite within biotite-rich alteration zones in gabbro.

At Henriksnäs, U–REE mineralisation occurs within biotite-muscovite-K-feldspar-sillimanite gneisses containing andalusite porphyroblasts. Here, monazite-(Ce), brannerite, fluorapatite, uraninite and zircon occur as disseminated grains and aggregates.

Compared to the Olserum-type REE mineralisations dominated by the REE phosphates xenotime-(Y) and monazite-(Ce), these lesser-known occurrences display more complex REE–Y–U/Th–Ti/Nb–Fe-bearing assemblages and variable textures. Preliminary data suggest previously undocumented compositions within the crichtonite group; further quantitative WDS analyses are needed to assess this variability. These findings provide new insights into the mineral diversity and critical mineral potential of the Västervik region.

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P4.16

Critical metal mineral systems in Canada's eastern Shield: Linking Mesoproterozoic alkaline magmatism to REE, Zr, Nb, and Sc enrichment

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Rare earth elements (REE) and other critical metals, including scandium (Sc), zirconium (Zr), niobium (Nb), and yttrium (Y), are essential raw materials in clean energy transition, advanced technologies, and national security. Canada hosts world-class rare-metal mineralization in Mesoproterozoic alkaline to peralkaline intrusions (~1460–1240 Ma) of the eastern Canadian Shield, yet the magmatic and tectonic evolution of these systems remains poorly constrained.

This study is focused on two globally significant mineralized systems: the ca. 1240 Ma Strange Lake REE–Zr–Nb deposit, one of the largest potential sources of heavy REE; and the ca. 1410 Ma Crater Lake Sc–REE deposit (formerly known as Misery Lake), which is hosted by the Mistastin Batholith (1439–1410 Ma) and amongst the most promising primary scandium resources. New SHRIMP U–Pb zircon ages from the Mistastin Batholith (1418–1417 Ma) confirm that magmatism within this complex was prolonged and episodic, spanning nearly 30 Myr. When integrated with existing and new ages from several much older Neoproterozoic to early Paleoproterozoic mafic to intermediate intrusions (e.g., Nekuashu and Pelland intrusions) near the Strange Lake deposits, together with regional geochronology, these results support a model of long-term mantle enrichment, initiated during Paleoproterozoic subduction-related processes and later tapped by Mesoproterozoic intraplate alkaline magmatism.

This framework helps explain the contrasting mineralization styles: cumulate-hosted Sc and LREE in ferrosyenite at Crater Lake, versus extreme fractionation-driven REE–Zr–Nb enrichment in evolved peralkaline granites at Strange Lake. Rather than isolated events, these systems represent stages of a protracted tectonomagmatic evolution that progressively concentrated incompatible elements across a fertile lithosphere over ~200 Myr.

These insights have direct exploration implications. They highlight the need to evaluate the entire magmatic spectrum of alkaline to peralkaline complexes, from early cumulates to late evolved granites, and to consider broader lithospheric enrichment processes in exploration models. The eastern Canadian Shield thus provides a natural laboratory for refining global strategies for critical raw materials in intraplate magmatic settings.

O6.1

Application of a Structured Anthropogenic Resource Assessment (SARA) for UNFC

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In recent years, the use of secondary raw materials from anthropogenic resources has gained in importance. Against this backdrop, the European Commission recently adopted the Critical Raw Materials Act (CRMA) to strengthen the EU's supply chain for these materials. It includes reporting of CRMs in primary and secondary raw material projects in line with the United Nations Framework Classification for Resources (UNFC). While the mining industry has well-established guidelines for classifying and reporting projects' maturity, there are currently no similar guidelines for developing and classifying recovery projects from anthropogenic resources using the UNFC. Furthermore, the classification of projects in the recycling sector is unknown, and project developers require support to implement it.

As part of the Horizon Europe project FutuRaM, a standardized procedure for defining, evaluating, and classifying projects was developed. The structured assessment of anthropogenic resources for the UNFC (SARA_4_UNFC) takes into account three important development phases, from the project idea to implementation: screening, pre-feasibility, and feasibility phase. A user-friendly web-based tool was developed that guides project developers through a 5-step screening phase and a 7-stage procedure for the pre-feasibility, and feasibility phases. A set of controlling factors is defined for each of the six criteria relevant to the classification of a project: economic, environmental, social and legal aspects for the E-axis, technical feasibility, including infrastructure for the F-axis, and level of confidence in the quantities for the G-axis. This ensures consistency, transparency, and comparability between projects. At the end of each phase, the results are summarized with an E-F-G class. The report includes the categorization of factors that help identify the strengths and weaknesses of projects. Decision-makers can then decide whether to continue or discontinue the project. The advantage of this approach is that it can be used for both mining waste and end-of-life materials. The comprehensive approach to evaluating recycling projects has been tested in various case studies, developed by different members of the FutuRaM team. It also includes several mining waste case studies.

The structured data collection format enables data to be transferred from the local to the regional and national levels. It also provides a uniform structure for assessing economic, environmental, and social impacts at the regional level and helps identify opportunities, potential shortcomings, and bottlenecks. This structured approach enables effective communication of results to various stakeholders, such as operators, investors, authorities, policymakers, and the public, and provides important information for evidence-based decision-making. In summary, the UNFC provides a uniform framework for responsible resource management and strategic decision-making.

O6.2

Mining Waste in Sweden its economic potential and UNFC classification

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We present a comprehensive data base on Swedish mining waste sites. We also present concept studies, with sampling protocols, including dense drilling of tailings sites, like Adak tailings dam. It was shown that for Cu extraction sites, tailings had in most cases no economic viability with often of the order of .1% of remaining copper. 3D models of the waste sites show that there might be significant differences of raw materials in different parts of the tailing either at depth or in different tailings areas. This depends on either change of ore type or extension of the tailing or change in process. The value of the raw materials in these sites are in most cases too small to even consider extraction. Iron apatite tailings on the other hand contain interesting amounts of P₂O₅ and REE. Like wise there are complex metallic residues containing interesting amounts of raw materials. The sites, though with low tonnages, might act as support to exploration of nearby primary deposits indicating mix of critical raw materials, base metals and precious metals. A model for UNFC classification of the tailings and waste rock sites is also presented building upon other parts density of sampling and uncertainties in the grades and tonnages. We select waste for UNFC based upon its relation to grades considered prospective in primary operations. For tailings we see that out of the EU critical raw materials list then remains Bi, Co, Ga, P, REE+Y, V, W, Cu that can be considered for UNFC classification. Further, Zn, Au and Ag also show elevated levels contributing to the exploration potential. However, critical raw materials are in most cases by-products and the final prospectivity is from the combined potential in value. In comparison to primary the total value of raw materials are low. The future economic viability will depend of course upon commodity prices and cost of extraction and investments. As for data base the in Futuram and GSEU developed Min4EU for mining waste is adequate for the needs of the CRM Act.

06.3

FUTURAM: mining waste characterization methods applied to case studies in Sweden

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FUTURAM is a HORIZON EUROPE Research and Innovation 4-year project (2022-2026) with main objectives to map the supply of Critical Raw Materials (CRM) obtained from recycling of six waste streams: batteries, electrical and electronic equipment, vehicles, mining waste, slag and ash, and construction and demolition waste, and to establish a methodology, reporting structure, and guidance to improve the raw materials knowledge base up to 2050. Apart from building a common database with Secondary Raw Materials (SRM) in Europe, several case studies were carried out to test different methods and approaches in order to evaluate the mineral potential and economic value of historic and current mining waste volumes. Additionally, UNFC has been applied to SRM projects to test, develop, validate and demonstrate the procedures in line with UNFC to enable fact-based decision making for their exploitation.

The Håkansboda mining field located in west-central Sweden is a historic mine where Cu and Co ore was mined since the XV century. The Håkansboda polymetallic Cu-Co sulphide deposit is a SVALS-type, a stratabound Cu-Co (Fe, Sb, As, Bi, Ag and Au) mineralisation hosted in the so-called Håkansboda marble. It contains massive chalcopyrite-pyrrhotite rich ore bodies with surrounding less massive mineralization zones with various textures and composition.

Several groups of methods have been tested at Håkansboda: sampling routines, geochemical and mineralogical methods, and waste beneficiation methods. Geochemical methods gave an overview of the chemical composition of the waste rocks with special emphasis on metals and critical raw materials. Mineralogical methods were used for determining the phases (minerals) in which metals occur and in what parageneses/associations. The preliminary beneficiation tests allowed us to predict possible extraction and processing technologies and validate the potential of waste for further extraction, including economic-related factors, such as the grade which can be obtained. At last, UNFC classification has been developed upon the basis of quality of the parameters/controlling factors as well as their uncertainties supporting the level of confidence.

O6.4

Insights into geostatistical modelling of mine tailings and sampling methodologies from the Otanmäki ilmenite tailings storage facility project

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Interest towards extractive waste sites as sources of secondary raw materials has substantially increased in recent years (European Commission 2024), highlighting the need for robust investigations of their resource potential and the methodologies used for the assessment. The Otanmäki tailings storage facility (TSF) in Central Finland, fully owned by Otanmäki Mine oy, provides a suitable environment for testing the effect of spatial density of sampling in resource modelling, as well as for comparing different sampling methods (Leskelä et al. 2025).

Three sample collection methods were tested at the Otanmäki TSF: a tube-sampler with a valve, a flow-through blade and an auger drill. The tube-sampler was found to be the most suitable method for collecting samples from the Otanmäki TSF.

Utilizing both previously existing and new sample data, multiple resource models were created within different scales, to study the effects of varying the number of sample points (low- to medium- to high-density of sampling) to the grade and tonnage model. In the most extreme model, sample point density was increased up to a 25 x 25 m grid from the pre-existing 100 x 100 m grid. The modelling results show that adding sampling points did not significantly change the final grade and tonnage across the any of the models at the Otanmäki TSF. This indicates that for the Otanmäki TSF, the existing 100 x 100 m sampling grid was sufficient to have a high confidence in the resource quantities within.

The pros and cons of each sampling method must be weighed based on the conditions, such as moisture conditions, depth of tailings, and available time, on a case-by-case basis. The Otanmäki ilmenite tailings are relatively homogenous, exhibiting good horizontal grades continuities and a low nugget effect, which is unlikely to be the case for other waste sites where there may be considerable heterogeneity and spatial complexity in the waste material. Regardless, a similar approach could be adopted in studying other extractive waste sites to test what the required sampling density is in order to produce high-confidence estimates in a cost-efficient manner. A spatial sampling sensitivity test can be conducted in a smaller portion of the waste area without requiring dense sampling across the entire site.

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O6.5

Tungsten source and mobility in Legacy Mine Tailings: Implications for Sustainable Re-Mining and Waste Management

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Tungsten (W) is classified as the most economically important EU-critical raw material, and extraction is expected to increase within the coming years. Tungsten is also classified as an emerging contaminant of concern due to the unexpected high mobility in the terrestrial environment and the adverse impact on human health (Strigul 2010). Knowledge regarding W geochemistry is lacking, but is crucial to develop efficient extraction methods and mine waste management strategies. Legacy mine tailings from Scandinavia's largest W deposit have been studied for more than 10 years to elucidate geochemical conditions mobilizing W (Hällström et al. 2020), and the possibility of re-mining W from the waste after 100 years of storage (Mulenshi et al. 2021). Two different Tailings Storage Facilities (TSF) holding waste from the same ore were elucidated: (i) *Smaltjärnen* (1912-1963) was deposited dry for more than 100 y, (ii) *Morkultjärnen* (1969-1989) was water saturated and covered with 2 m of peat. Tailings from different depths in both TSFs were studied with geochemistry and mineralogy (optical microscopy, SEM-EDS, XRD, automated mineralogy, and microprobe analysis). Extraction methods such as enhanced gravity separation and leaching while grinding were developed to improve extraction efficiency. This is one of the first field studies to mineralogically demonstrate that W had mobilized from scheelite under alkaline, reduced conditions. This resulted in very high concentrations of dissolved W in the groundwater, surface water and drinking water from the TSF of *Morkultjärnen*. The genesis of scheelite weathering was revealed by weathered morphology and decreased W in the crystal lattice. In tailings from the TSF of *Smaltjärnen*, the WO₃ recovery reached up to 90% during leaching while grinding. This study shows that the traditional mine waste management approach, which utilizes an anoxic environment, is unsuitable for W-bearing waste. Instead, re-mining can be a suitable remediation strategy. From an economic perspective, the low quantity of tailings at the site needs to be considered (3300 tonnes of WO₃). Furthermore, new mines should consider separating tungstates from sulfides during mine tailings storage to minimize environmental impact, as they are stable under various redox conditions.

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O6.6

Composition of fly ash from a grate firing municipal solid waste incineration plant with a focus on the composition and distribution of zinc-bearing minerals

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Municipal solid waste incineration (MSWI) generates fly ash as a minor but chemically and mineralogically complex byproduct that is considered both an environmental risk and a secondary resource. This study investigates the mineralogical composition and grain morphology of fly ash collected from eight outlets in the combustion chamber, boiler and bag filter of the ARGO MSWI plant in Roskilde, Denmark, using combined bulk rock geochemistry, automated quantitative mineralogy (on a Scanning Electron Microscope) and X-ray diffraction analyses with the objective is to understand the nature and distribution of zinc-bearing minerals.

Rounded grain shapes with holes and inclusions suggest that most of the incinerated material was molten or vaporized. Mineralogical analyses show that fly ash particles exhibit a consistent mineralisation sequence in rims around the grains —silicates, oxides, carbonates, sulfates, and chlorides—reflecting the order of crystallization during cooling. Agglomeration is driven mainly by alkaline phases such as arcanite and halite, that bind smaller particles into loosely structured clusters. Zincite formation is favored in alkaline, intermediate temperature zones (ca. between 800-300°), often co-occurring with arcanite. Zinc concentrations rise from 0.5 wt% for the combustion chamber fly ash to 5 wt% in the bag filter fly ash, with a notable transition from Zn-oxides in the boiler to Zn-silicates in the bag filter. The coarse fraction consistently shows higher Zn content than the fine fraction from the same outlet, indicating that agglomeration processes concentrate metals. The high concentration of zinc-silicates in the bag filter may be explained by zinc being volatile until reaching the bag filter and subsequently forming hydrated silicates under moist conditions facilitated by the presence of halite.

The study confirms that mineralogical zonation in MSWI fly ash is governed by thermodynamic conditions, particularly mineral freezing points, and local chemical and physical environments. These findings have direct implications for resource recovery: the spatial distribution and mineral associations of zinc-bearing phases support targeted extraction strategies, especially from the bag filter fraction. This work provides a detailed mineralogical framework for understanding fly ash formation in MSWI systems, which can serve as a basis for modelling of fly ash formation and recovery processes in the future.

P6.1

Rare earth element trends and their relationship to mineralogy in iron-oxide-apatite (IOA) mine waste: a case study of the Jan-Matts stamp sand repository (Grängesberg, Sweden)

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With the inception and implementation of the European Commission's Critical Raw Material Act, the interest in re-evaluating formerly subeconomic raw material resources has drastically increased to boost the production of critical raw materials (CRMs). One such type of non-traditional CRM source is historic mine waste facilities (MWFs), as previously discarded gangue mineral phases can host elements which are today classified as CRMs. The latter is the aim of this study.

When the Grängesberg iron-oxide apatite (IOA) deposit was mined, only the iron oxide minerals were targeted for extraction, leaving concentrated amounts of apatite in the waste material – the Jan-Matts stamp sand repository being one such MWF. Apatite can incorporate significant portions of rare earth elements (REEs) in its crystal lattice, making the apatite in mine waste a tempting target as a source of REEs. F-Apatite and Ce-monazite are the most abundant REE-associated minerals identified in the mine waste material. With detailed laser ablation inductively coupled plasma mass spectroscopy (LA-ICP-MS) trace element analyses, the distribution of REEs within apatite and monazite found in the mine waste material is explored.

Apatite is commonly found within the mine waste material as separated grains, whilst monazite predominantly occurs as micro-inclusions within the apatite. Independent monazite grains are only found in trace amounts (i.e., sporadic grains). The LA-ICP-MS analyses of apatite and monazite clearly show that monazite contains higher contents of all REEs, except for Lu. Measured apatite contains, on average 4,972 ppm light REEs (LREEs), 823 ppm medium REEs (MREEs), and 3,134 ppm heavy REEs (HREEs). Monazite contains, on average, 60 wt% LREEs, 2.5 wt% MREEs, and 1.2 wt% HREEs. Chondrite-normalized REE patterns demonstrate the presence of multiple apatite populations within the mine waste. Relatively to the total $\Sigma\text{REE}+\text{Y}$ of each mineral, apatite contains more HREEs compared to monazite, and would thus be particularly significant for the recovery of HREEs.

Average contents of $\Sigma\text{REE}+\text{Y}$, ΣLREE , ΣMREE , and $\Sigma\text{HREE}+\text{Y}$ of whole rock, apatite, and monazite data indicate that apatite, not monazite, is the most prominent mineral controlling REE contents in this mine waste. This is also evident through the comparison of the shares of the individual REEs (e.g., Pr, Nd, Tb, and Dy) when normalized to the total sum of rare earth elements including yttrium ($\Sigma\text{REE}+\text{Y}$). By combining whole rock data and previously published mine waste tonnage estimates, the total REE resource of the Jan-Matts MWF can be estimated and put into context with active REE mining operations. The combined results of this study will aid in the evaluation of other, both historic and active, IOA MWFs, where REE-bearing apatite and monazite are left behind as waste.

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07.1 (Keynote)

On the major structures and evolution of the Precambrian rocks of the western East European Craton: new results and developments

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Bogdanova et al. (2015) outlined major structures and developed a new tectonic model for the Precambrian of the Baltic Sea region based on the available geophysical, geochemical, isotope data and PT calculations. Key areas were chosen in Lithuania and neighboring countries for further model testing and improvement.

The Mid-Lithuanian domain was subdivided into the NW (1.83-1.86 Ga) and SE (1.82-1.87 Ga) domains. They are intruded by ca. 1.8-1.81 Ga granitoids and 1.76 Ga microgabbro-norites, respectively. Despite the difference in metamorphic degree, gabbros, diorites and granitoids tend to belong to the same magma fractionation series, supported by the Sm-Nd and Rb-Sr data.

U-Pb zircon datings confirmed the “true” Svecofennian age of ca. 1.89 Ga for the Lithuanian part of the Latvian-East Lithuanian (LEL) belt, which hosts the Varena Iron Ore deposit (VIOD), and its continuation to Latvia (ca. 1.89 Ga for the Subate orthogneiss).

New U-Pb-Th monazite dating and thermodynamic modelling revealed that the earlier recognized ca. 1.8-1.79 Ga high-grade regional metamorphism in most cases, is entirely overprinted or absent. Mainly thermal metamorphism of ca. 1.70-1.72 Ga was more widespread and followed by ca. 1.60 and 1.50 Ga reworking stages.

New magmatic and metamorphic ages of 1.74-1.76 Ga were obtained from the slightly metamorphosed diorites in E and S Lithuania. Earlier, the hydrothermal overprint on the Varena iron ores at ca. 1.71 Ga was recorded by zircon, baddeleyite, and monazite grains.

Sedimentary origin of the Kybartai gneisses in the S WLG was confirmed by the isotopic investigations. However, their revised PT conditions did not reach granulite facies, suggesting a further revision of the West Lithuanian Granulite (WLG) domain.

To sum up, the LEL complexes may be correlated with similar complexes in Estonia, Finland, and Sweden. The MLD correlates well with the oldest series of the Trans-Scandinavian Igneous belt (TIB) described by Salin et al. (2019) as TIB0. The WLG should be revised, and its magmatic complexes compared with the magmatism in Sweden and Poland. The newly recognized 1.74-1.76 Ga magmatism may be an important issue for further evolution of the latest stages of the entire TIB, as well as for ore mineralization in the VIOD and surrounding areas.

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07.2

Phanerozoic evolution of Fennoscandia: Evidence from apatite fission track, fluid flow and geodynamic data in Finland and Estonia

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New apatite fission track (AFT) data from Estonia together with previously published data from Finland, all from crystalline basement drill core, constrain the Phanerozoic thermal history. Models show a consistent pattern of heating from Cambrian to end-Carboniferous, with peak paleotemperatures of $60 \pm 10^\circ\text{C}$ when sediment cover was ~ 0.5 km thicker in the Baltic Paleobasin and ~ 1.5 km over Precambrian basement in Finland. Prior to the Phanerozoic, the Fennoscandia basement was exhumed to a peneplain by late Neoproterozoic. The evolution of Phanerozoic sedimentary cover can be linked to (1) the Scandinavian Silurian–Devonian Caledonian orogeny, (2) foreland basin and foreland uplift bulge development, (3) pre-drift extension and lithospheric uplift from Permo-Triassic to Cretaceous, and (4) Cenozoic rift-phase uplift following North Atlantic opening at ~ 54 Ma. In the Devonian, Caledonian mountains attained elevations of ~ 7 – 8 km, causing significant lithospheric elastic flexure resulting in a 6–7 km deep foreland basin and ~ 500 m of foreland bulge uplift affecting Fennoscandia and the Baltic Paleobasin. The flexure relaxed and the foredeep basin was partly inverted as the mountain range exhumed and eroded during late orogenic collapse (~ 400 Ma). The present shield area in Finland may have outcropped for a short time in the Devonian during the Caledonian forebulge phase but was covered shortly thereafter with sediments. The cover persisted until the final exhumation of Finland in the Mesozoic – Cenozoic. Some AFT data indicate hydrothermal disturbance by expulsion of hot fluids from the Caledonian thrust belt into the unconsolidated basal Cambrian sediments and crystalline basement. This craton-wide flow resulted in the precipitation of Devonian calcite-fluorite-Pb-Zn veins, Mississippi Valley type Pb-Zn deposits in the Swedish Caledonian front and dolomitic alteration of Ordovician-Silurian limestones in Estonia. Moreover, our model contributes to the interpretation of the evolution of topography in Norway and distribution of deep biosphere in Fennoscandia.

07.3

Evidence for deposition and removal of Phanerozoic covers across the Fennoscandian Shield

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Shield areas such as Fennoscandia, Guiana and Canada are often considered as stable cratons, undergoing long-term emergence and denudation due to buoyancy. This interpretation is influenced, in part, by the lack of sedimentary cover above the exposed Precambrian basement. However, integrating thermochronology data with geological and geomorphological observations shows that in many cases the lack of cover is the result of a history of burial followed by exhumation (Green et al. 2022a).

The evolution of Fennoscandia following the early Devonian collapse of the Caledonian mountains is a matter of debate, due largely to the scarcity of post-Caledonian cover rocks. Therefore, consideration of the evidence of rocks that were formerly present but have since been removed, provides a more complete understanding. Green et al. (2022b) reported apatite fission-track data and associated thermal history constraints in samples of Precambrian basement, younger sedimentary cover, Paleozoic and Mesozoic igneous rocks from outcrops and boreholes (up to 6 km depth; e.g. the OTN boreholes near Helsinki) across Fennoscandia. They interpreted the data in terms of multiple episodes of cooling (each representing kilometre-scale exhumation) over the last 1100 Myr. Following the Caledonian Orogeny, key episodes began in the late Carboniferous, Middle Triassic, Middle Jurassic, mid-Cretaceous and early Miocene.

These episodes, varying in magnitude, are recognised across Fennoscandia, and their effects are documented in the stratigraphic record and as prominent regional peneplains. The results define a history involving repeated episodes of regional burial and exhumation. Results from Finland record the same events recognised in Norway and Sweden and are not consistent with long-term cratonic stability.

For example, km-thick sedimentary covers of Cambrian to Carboniferous sediments were present above the Sub-Cambrian Peneplain prior to late Carboniferous exhumation in Finland and southern Sweden. Following renewed deposition, mid-Cretaceous exhumation resulted in the formation of a deeply weathered, hilly peneplain over large parts of Sweden and Finland and thus in the removal of most of this cover.

The post-Caledonian exhumation episodes defined in Fennoscandia and in the adjacent sedimentary basins, are broadly synchronous with similar events in Greenland (Japsen et al. 2024).

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07.4

U-Pb geochronology and Hf isotopic systematics of Estonian Paleoproterozoic granites and surrounding gneisses

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The Paleo- to Mesoproterozoic crystalline basement of Estonia consists predominantly of metamorphic and plutonic formations, intruded by anorogenic rapakivi granites that cut the older Svecofennian metamorphic complex. Structurally, the Estonian basement comprises two major domains: the northern part, dominated by amphibolite facies metamorphic rocks, and the southern part, where metamorphism reached granulite facies conditions (Puura et al. 1983; Soesoo et al. 2004).

Geophysical surveys and drilling have revealed five stock-like rapakivi granite plutons beneath a 150–300 m thick Late Neoproterozoic and Early Paleozoic sedimentary cover in Estonia (Soesoo & Niin 1992; Soesoo 1993). All Estonian rapakivi granites display A-type geochemical characteristics (Soesoo & Hade 2012). The crystallization ages of several rapakivi plutons are known, but some intrusions record multiphase emplacement histories. For example, the Märjamaa pluton yields a U-Pb zircon age indicate that the main intrusive phase occurred at 1.629 Ga, followed by later phases at 1.626 Ga and 1.622 Ga. The Neeme granitoids yield a U-Pb zircon age of 1.634 Ga, the Taebala rocks 1.648 Ga, and the Ereda rocks record two age groups at 1.642 and 1.627 Ga.

The magma sources and emplacement processes of the Estonian rapakivi plutons remain poorly constrained. In this study, we present new U-Pb zircon ages and Hf isotopic data from selected granites and their host gneisses in northern Estonia. Hf isotopes are particularly valuable for identifying magma sources. Our results show that rapakivi and migmatitic granite samples yield ages of 1.680–1.650 Ga, with ϵ_{Hf} values ranging from slightly positive values to –3.5. Three samples of migmatitic gneiss contain zircons dated to 1.900–1.835 Ga, with predominantly positive ϵ_{Hf} values, indicating a juvenile origin. A possible leucosome from the gneiss yields zircons with typical rapakivi ages (1.68–1.65 Ga) and Hf isotope compositions consistent with those granites.

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07.5

Rare earth element distribution and enrichment in the Mesoproterozoic Naissaare rapakivi stock, northern Estonia: insights from a deep weathering profile

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With the introduction of the EU Critical Raw Materials Act, all member states are required to prepare exploration plans for critical metals to reduce reliance on external imports. In this context, the Estonian government has initiated a re-evaluation of CRM potential in the largely overlooked crystalline basement of Estonia, buried under sedimentary cover at depths varying from 150 m in the north to more than 700 m in the south. In this contribution, we investigate the behaviour of rare earth elements (REE) in the Naissaare rapakivi stock, northern Estonia, focusing on the REE distribution in the weathering profile developed on the crystalline basement in Neoproterozoic (Liivamägi et al. 2014).

Samples derive from the new geothermal drillhole intersecting granitic basement at 155 m depth below ground surface for 350 meters to a maximum depth of 505 m. The 1629 ± 7 Ma Naissaare stock (i.e., coeval with Wiborg and Ahvenisto rapakivi intrusions in southern Finland, Rämö et al. 1996) is K-porphyry granite, comprised of in decreasing proportion microcline phenocrysts, quartz, plagioclase, biotite, with accessory hornblende, muscovite, magnetite, ilmenite, apatite, epidote and fluorite. Naissaare rapakivi is not of rapakivi proper *sensu stricto* due to the absence of rapakivi structure; however, geochemically it belongs to ferroan, alkalic, weakly peraluminous A-type rapakivi granite.

The uppermost part of the rapakivi profile is characterised by an unusually thick weathering profile extending 105 m below the granitic basement surface. Potassium corrected Chemical Index of Alteration (CIA-K) values decrease from 57 to 51, indicating that the most strongly altered upper part of the profile has been removed by erosion prior to deposition of Ediacaran terrigenous sediments. This trend is mirrored by systematic changes in Ba/Rb and Rb/Sr ratios. The total REE (Σ REE) concentration increases with depth through the weathering profile from 470 to 917 ppm (average parent rock 550–650 ppm). The redox-sensitive Ce is not decoupled from other REE, suggesting that only the deeper part of the weathering profile has survived. The chondrite normalised REE patterns of the weathering crust are homogeneous with LREE enrichment over HREE and only minor to absent Eu anomaly, with no significant fractionation between the weathered and parent rock.

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07.6

Crustal Structure of the Fennoscandian Orogen Beneath Baltic Sea proper and Sediment Cover: Insights from Gravity and Magnetic Anomalies.

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Since 2008, the European Commission has pursued the Raw Materials Initiative to secure long-term access to critical raw materials (CRMs), with updated CRM lists released in 2011, 2014, 2017, 2020, and 2023. Many of these CRMs are sourced from the Fennoscandian Shield, whose tectonic and metallogenic evolution remains only partly understood.

This study examines the crustal structure of the Fennoscandian orogen beneath areas concealed by water (the Baltic Sea) and thick sedimentary sequences (the Baltic States), where crystalline basement outcrops are absent. The objective is not a direct assessment of metallogenic potential, but the development of a structural framework to support future resource evaluations.

Magnetic anomaly data were compiled from the Fennoscandian Shield magnetic maps (Korhonen et al. 2002) and digitized Soviet-era aerogeophysical reports (1968–1980) covering the Baltic States. The used grid of free-air gravity anomalies was initially constructed to compute the TUT solution for the Baltic Sea Chart Datum BSCD2000 quasigeoid model (Liebsch et al. 2023). Free-air anomalies were reduced to Bouguer anomalies using the TUT solution's associated digital topographic elevation and bathymetric depth model (Varbla 2002).

To resolve the vertical architecture of the crust, we integrated published deep seismic and seismological data with available petrophysical datasets. These inputs enabled the construction of an inverse crustal model, allowing refined interpretations of tectonic domains and their spatial relationships beneath the concealed segments of the Fennoscandian orogen.

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07.7

Crustal thickness of Estonia – results from seismic receiver function method and gravimetry

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Distant earthquakes provide valuable data for studies on inner structure of the Earth. The depth of the Moho or Mohorovičić discontinuity, the boundary between the crust and the upper mantle can be estimated using teleseismic P-wave receiver function analysis, a technique that uses converted seismic phases to detect velocity contrasts at depth.

Thanks to the extension of the seismic network of Estonia from three to over ten stations during recent years, an ample dataset of teleseismic records has been gathered enabling us to compile a contour map of crustal thickness within Estonia. Data from a few seismic stations in neighbouring countries were used for added coverage.

Previous estimates of crustal thickness in the region have relied primarily on gravimetric, magnetic, and sparse deep seismic sounding (DSS) data, often resulting in inconsistent interpretations and limited resolution. This work offers an independent seismic perspective. The results show considerable variation in Moho depth across Estonia, ranging from 46 km near the Tallinn region in the north to about 61 km in the southeast. Instead of broad regions of uniform crustal thickness, the map reveals strong lateral changes over relatively short distances. A distinct northwest-southeast trending boundary is observed: Moho depths are deeper south of this boundary and much shallower to the north.

An important finding of this study is the discrepancy between seismic and gravimetric interpretations. In general, lower Bouguer anomaly values are expected in regions of thicker crust, as the larger volume of low-density crustal rocks reduces the gravitational effect relative to the denser mantle. However, this principle does not align with the Bouguer anomaly pattern observed in western Estonia. This suggests that a meaningful correlation between gravity field patterns and the seismically defined Moho requires consideration not only of the Moho geometry, but also of the internal structure and tectonic framework of the crust. These results highlight the importance of integrating seismic observations. Despite uneven station coverage in southern Estonia, the analysis demonstrates the value of receiver functions for resolving subtle crustal features in stable continental settings. The findings support future efforts to combine seismic methods with gravity data into a more comprehensive geophysical model of the Estonian lithosphere.

07.8

Comparing the iron-ore rich regions of Central Latvia and Bergslagen, Sweden, using magnetic and gravity datasets

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The Precambrian crystalline basement of the central part of Latvia is thought to host considerable amount of iron ores, as indicated by significant magnetic anomalies and high magnetite content in the core material from deep boreholes. In most cases, there is not more than one or two boreholes at each of the magnetic anomalies, and even then they uncover only the very top of the basement, which greatly limits the interpretations. Most of the studies were conducted more than four decades ago - since then any significant exploration efforts have been hindered by the approximately 500-1000 meters thick Phanerozoic sedimentary cover and the drilling costs associated with it. No new local studies in the Central Latvia region have been done, however, relatively recent complex regional studies have suggested that the well explored mining region of Bergslagen in Sweden and the Precambrian basement of Central Latvia may be a part of the same microcontinent (Bogdanova et al. 2015).

Based on this interpretation, we attempt to add new insight by comparing the magnetic and gravity datasets of both regions. We start with a more regional view using the world magnetic and gravity data compilations, which show the potential fields at altitudes of five and four kilometers, respectively. Then we look at the near surface survey datasets for a more detailed view. Upward continuation transformation is applied to the Bergslagen dataset to bring the datasets of both regions to a similar altitude above the crystalline basement to allow for a more direct comparison. Various grid derivatives give useful information for further characterization of the similarities and differences between the two regions. We note that the magnetic intensities are significantly higher in the Central Latvia region despite the thickness of the sedimentary cover, but the shapes and sizes of the anomalies are similar. Finally, we attempt a careful estimation of the depth of the sources, and discuss the possible implications of our findings.

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07.9

Ore-associated magnetic anomalies in Estonia and Latvia: Significance of remanent magnetisation

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Despite the thick sedimentary cover, magnetic field maps of Estonia and Latvia show prominent high-amplitude anomalies originating in the crystalline basement. Over the past century, basement mapping has involved drilling deep boreholes to study mineralogical and chemical composition and the ore potential of structures causing these anomalies. Many studies revealed elevated metal concentrations and linked anomalies to the physical properties of source rocks.

The magnetic anomaly of a geological structure depends on the magnetisation contrast with the surrounding rocks, the source volume, and the depth. Magnetisation is a vector quantity with induced and remanent components. We examined the magnetic susceptibility (controlling induced magnetisation) along with the intensity and inclination of remanent magnetisation in cores from Estonian and Latvian magnetic anomalies (Jõhvi 1 and 2 [Jõhvi, NE Estonia; Plado et al. 2020], F188 [Uljaste, NE Estonia; Krull 2021], Vīķi GK-2P and Staicele 1 [Staicele, N Latvia], Gārsene 2A [Gārsene, S Latvia], Strenči 3 [Strenči, N Latvia]), and compared the results with previously reported data.

Magnetic susceptibility correlates reasonably well with data from past century reports. Compared to recent measurements, the older data are often more complete due to lost core material. By contrast, few immediate post-drilling measurements of remanent magnetisation exist, limiting vector characterisation. Recent measurements indicate that remanent magnetisation dominates over induced magnetisation in most cases, exerting primary control on the surface expression of ore-related magnetic anomalies.

For sulphide ores, pyrrhotite remanence may exceed induced magnetisation by several orders of magnitude, making it almost entirely responsible for the associated magnetic anomaly. In magnetite ores, remanence predominance over induced magnetisation indicates a significant contribution from single- and pseudo-single-domain magnetite (Dunlop 1990). Thus, it is not the quantity of magnetite but its magnetic properties that generate the anomalies, and the amplitudes of these anomalies do not directly correspond to the amount of ore.

Acknowledgments

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07.10

Trace elements of magnetite in the Jõhvi magnetite-rich gneisses in north-east Estonia: implications for the genesis and alteration of iron mineralization

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The origin of the Jõhvi Magnetite Anomaly (JMA) in northeastern Estonia has been debated for decades, with proposed models ranging from skarn and metasomatic processes to metamorphic or volcanogenic-sedimentary origins. More recent observations of banded magnetite–quartz layering and garnet-rich assemblages have suggested a volcanogenic-hydrothermal Algoma-type banded iron formation (BIF) precursor. Yet, the genetic interpretation of the JMA has remained unresolved.

In this study, we investigate the genesis of the JMA using petrography and in situ magnetite trace element geochemistry (SEM, LA-ICP-MS), supported by principal component analysis (PCA). The results show that magnetite compositions cluster into distinct geochemical groups controlled by host lithology. Magnetite hosted in garnet–pyroxene rocks retains the least altered geochemical signature, consistent with an Algoma-type BIF origin, whereas magnetite from feldspar-rich rocks records extensive metasomatic modification and migmatization.

Our data indicate that JMA mineralisation formed initially as an Algoma-type BIF under hydrothermal conditions, but was later strongly modified by two overprinting events: (1) granulite-facies regional metamorphism, and (2) metasomatic hydrothermal alteration associated with migmatization, leading to partial melting and magnetite recrystallisation. These processes obscured primary genetic signals and produced geochemical overlaps with IOCG-, porphyry-, and other hydrothermal-type deposits.

Comparisons with iron ore provinces such as Bergslagen (Sweden) and Orijärvi (Finland) support the interpretation of a BIF precursor subsequently modified during major tectonothermal events of the Fennoscandian Shield. The study highlights both the metallogenic significance of the JMA and the limitations of magnetite trace element geochemistry when applied to strongly overprinted terranes. We emphasise that a multidisciplinary approach—combining petrography, geochemistry, and regional geological context—is essential to resolve the origin of complex Precambrian iron formations.

07.11

CRM potential of Estonian Precambrian basement: First mineral exploration insights from the DEXPLORE project

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The Estonian Precambrian basement is considered a southern continuation of the Fennoscandian Shield, and this yields potential similar to that of metal formations found in southern Finland and Sweden, especially with the Bergslagen province and the Uusimaa belt. It is overlain by a 100 to 780m thick cover of sedimentary rocks (Soesoo et al. 2020). Thus, the basement is unavailable for direct observations from the surface, and the present knowledge is based on information from cores from deep drillings and interpretation of potential gravity and magnetic fields. Significant anomalies of siderochalcophile, graphite-bearing gneisses have also been identified, where Cu, Pb, and Zn reach levels as high as 5.6% (Siim & Soesoo 2021). Therefore, mineralisation and ore potentials remain to be explored with deep-land investigations and could lead to the discovery of potential CRM sources for the EU.

In the DEXPLORE Horizon project framework, a characterisation campaign is being conducted in East Estonia, within the Alutaguse province, targeted at three areas where geophysical measurements revealed anomalies: Assamala, Haljala, and Uljaste (Solano-Acosta et al. 2025). The campaign aims to provide systematic mineral (SEM, LA-ICP-MS) and geochemical quantification studies (XRF, XRD, ICP-MS) over six drill cores. Main lithologies comprise amphibolite or felsic gneisses, quartzite, marble, and migmatites enriched in sulphides and graphite.

This study will present the first results, investigating metallogenic signatures and petrographic approaches for the development of ore models and comparison to neighbouring provinces.

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07.12

Alutaguse and Jõhvi Zones, North Estonia: Geochemical and Geophysical Evidence for Paleoproterozoic Back-Arc Evolution and Critical Raw Material Potential

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The North Estonian crystalline basement, buried beneath 100-780 m of Phanerozoic cover, hosts significant mineral potential within the Alutaguse and Jõhvi zones (Bogdanova et al. 2015; Soesoo et al. 2020). Historical geochemical datasets (e.g., Kivisilla et al. 1999), including major-element and spectral drill-core analyses, integrated with Bouguer gravity and magnetic interpretations (Solano-Acosta et al. 2023, 2025a–b), refine the tectonic and metallogenic framework of this sector of eastern Fennoscandia. Geophysical modelling of key anomalies highlights Uljaste, Assamalla, and Haljala, where high-intensity signals correlate with sulfide-graphite gneisses and quartzites (Nirgi & Soesoo 2021).

Metasedimentary units, dominated by garnet- and cordierite-bearing micaceous gneisses, display felsic UCC-like and intermediate-mafic PAAS-like signatures, while metavolcanics (amphibolites and pyroxenic gneisses) show subalkaline affinities. These features indicate a Paleoproterozoic back-arc setting (1.90-1.89 Ga) adjacent to the Uusimaa belt, followed by the accretion of Uusimaa and Häme at ca. 1.87 Ga (Bogdanova et al. 2015; Solano-Acosta et al. 2025). Comparative analysis reveals both geochemical and structural affinities with the South Svecofennian terranes. In contrast, the anomalies and multiphase sulfide mineralisation: chalcopyrite, sphalerite, galena, arsenopyrite; closely resemble VMS-style deposits of the Bergslagen region (Solano-Acosta et al. 2025).

Drill-core assays record up to 5.6% combined Cu-Pb-Zn in graphite- and sulfide-bearing gneisses, together with magnetite-rich iron horizons and notable Mn and Mo concentrations. The highest Cu-Pb-Zn values occur in amphibolite-graphite horizons, positioning them as key hosts for critical raw materials, including graphite, Ni, and Mn (Nirgi & Soesoo 2021). The Jõhvi zone further demonstrates metallogenic affinities with Bergslagen and Finland's Orijärvi district (Soesoo et al. 2020).

This study contributes to Horizon Europe DEXPLORE, which focuses on Alutaguse and Jõhvi zones in Estonia. Integrated geochemical and geophysical datasets provide the basis for new metallogenic models. These results strengthen correlations between North Estonia, the South Svecofennian terranes, and Bergslagen, while advancing exploration strategies to secure Europe's supply of critical raw materials.

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P7.1

Blind Uranium Mineralisation in Latvia: Occurrence and In-Situ Leach Potential

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Systematic surveying in Soviet times identified a number of radiometric and hydrogeochemical uranium anomalies in Latvia. These were tracked down at surface to thin bedrock sources in fish and organic-rich parts of Devonian clastic sediments. More significantly water well gamma logging and sampling highlighted the subsurface potential of the Talsi area of Kurzeme. This led to detailed drilling which intersected potentially commercial grades within reduced (grey) channel sediments of the Arukūla and Burtnieki Fms. Although these are peneconcordant in nature they appear related to oxidation/reduction features resembling in scale and type the roll front uranium deposits of interior USA or Kazakhstan. These roll fronts are susceptible to in-situ leaching technology that might ameliorate the difficulties for extraction posed by private mineral rights ownership in Latvia.

Detailed U/Ra analyses in the 1980s (Churyasov 1985) suggest multiple ages for the uranium deposition, 280, 170, 120, 35-70, 0-1 Ma reflecting diagenesis and stages of uplift.

The poster will illustrate the nature of known intersections, as well as outcrop features of uranium mineralisation and ultimate sources in the basement.

Acknowledgments

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P7.2

Crustal evolution of the concealed Precambrian complexes of Lithuania: A perspective from Lu-Hf isotopes in zircon

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A major part of the crystalline basement of Lithuania consists of domains that are increasingly younger towards the south: the Latvian-East Lithuanian (LEL), the Mid-Lithuanian domain (MLD) incorporated in the larger Mid-Baltic belt (MBB), and the West-Lithuanian Granulite (WLG) belt (Bogdanova et al. 2015). Skridlaite et al. (2021) further subdivided the MLD into north-western (NW) and south-eastern (SE) parts with more isotopically enriched and depleted mantle signatures, respectively.

Igneous rocks representing these domains were selected for Lu-Hf isotopes analysis in well-dated zircons, in order to reconstruct crustal evolution in the region. Additionally, two samples from felsic metavolcanic rocks and three samples from the Mesoproterozoic AMCG complexes were also analysed.

The calculated ϵ_{Hf} values for the LEL (1.87-1.89 Ga) range between -1.8 and +4.1 (average -0.1 ± 0.5 ; number of samples $n=5$). Zircons from the adjacent SE MLD (1.79-1.87 Ga) record slightly more radiogenic values ranging between -1.3 and +5.3 (average $+3.2 \pm 0.8$; $n=4$), whereas zircons from the NW MLD (1.80-1.86 Ga) on average have lower ϵ_{Hf} values (-3.2 to $+1.3$, average -0.8 ± 0.6 , $n=3$). Similarly, ϵ_{Hf} of -3.5 to $+0.7$ (average -1.1 ± 0.4 ; $n=4$) are observed in igneous rocks from the WLG (1.81-1.84 Ga). Felsic metavolcanics in SE Lithuania (1.80-1.83 Ga) have a near chondritic signature with ϵ_{Hf} between -1.2 and $+0.5$ (average -0.5 ± 0.3 ; $n=2$). The EMORB-like ca. 1.76 Ga microgabbro from the SE MLD (Skridlaite et al. 2021) also has near-chondritic zircons with ϵ_{Hf} ranging from -0.2 to $+0.8$ (average $+0.2 \pm 0.3$; $n=1$). The most negative ϵ_{Hf} were recorded for the AMCG suites (1.44-1.51 Ga), with values ranging from -8.0 to -3.6 (average -6.00 ± 0.5 ; $n=3$).

When plotted in the ϵ_{Hf} versus crystallisation age space, our data define a crustal evolution trend with a slope corresponding to a mafic source ($^{176}\text{Lu}/^{177}\text{Hf} \sim 0.019$), which would have separated from a depleted mantle reservoir at 2.8 Ga. We note the presence of juvenile magmatism at 1.8-1.9 Ga and a tendency for the western Lithuanian samples to have longer crustal residence times. The 1.76 Ga gabbro has a distinctly more chondritic composition, which plots well above the main crustal evolution trend defined by other samples. The crystallisation age of this gabbro was approximately synchronous with a ca. 1.75-1.79 active continental margin that was developing to the West (Krzeminska et al. 2021), and with the 1.7-1.8 Ga Sarmatia-Fennoscandia oblique collision to the East. We infer that compressive tectonics may have induced crustal stretching and mantle uplifting in SE Lithuania, resulting in the emplacement of gabbroic magmas with more radiogenic Hf isotope signatures.

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P7.3

The complex evolution of the Precambrian Varena Iron ore deposit, SE Lithuania: current state of knowledge

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The Varena Iron Ore deposit (VIOD) within the Latvian -East Lithuanian belt yields up to 220 million tons of iron ore. Several hypotheses have been suggested for its origin including possibility of layered mafic, ultramafic or carbonatite magmatism or metasomatic/hydrothermal processes but none of them could fully explain the complexity of rocks and ores. Very recently, some similarities with IOCG type deposits were noted (Siliauskas et al. in press).

Iron ores accumulated predominantly in former dolostones, which contained variable amounts of cherts or clastic sediments. The metasediments are enclosed in the metamorphosed magmatic rocks of felsic and intermediate composition and, in some places, covered by thin-layered gneisses. The enclosing augen gneisses of ca. 1.89 Ga underwent metamorphic reworking in the presence of Cl-rich fluid and experienced partial melting at temperatures ~750 °C ca. 1.75-1.77 Ga ago (Siliauskas et al. in press). The formation of salt melt may be responsible for iron ore and REE mobilization in the deposit.

The dolostones were intensively replaced by skarns (forsterite, enstatite, spinel and diopside) during a metamorphism of 750° C and 5-6 kbar. The fluid XCO₂, proximity to contact with alumina-silicate rocks and transportation of silica, magnesium and calcium in circulating fluids have caused the observed zonation. They were followed by water influx and amphibole producing reactions together with magnetite enrichment. Monazite, zircon and baddeleyite grains intergrown with the magnetite yielded a 1.71 Ga age (Skridlaite et al. 2024). They were followed by low temperature serpentinization, iddingsite and chlorite formation as well as accumulation of iron, phosphorus, REE and other ores.

New metamorphic and magmatic ages of 1.74-1.76 Ga obtained for the mafic and intermediate intrusions in the deposit and neighboring areas are semi-simultaneous with the metamorphism of the VIOD host rocks and might have triggered later skarnation. Small homogeneous monazite grains and rims in the studied calciphyre were dated at ca. 1.54 Ga. Zircon and titanite dating records slightly younger ages of 1.48 and 1.49 Ga, respectively (Siliauskas et al., in press). These findings suggest that the Mesoproterozoic reworking coinciding with the emplacement of the Mazury AMCG suites and the Kabeliai intrusions further south is quite ubiquitous.

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P7.4

Receiver Function and Gravity Inversion of the Moho in the Baltic States

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The Moho depth beneath the Baltic States can provide essential constraints on the evolution of Baltica palaeocontinent and its Proterozoic tectonic domains. Despite decades of seismic profiling, regional models remain inconsistent and poorly integrated. Here we combine P-wave receiver functions (RF) and 3D gravity inversion to improve spatial resolution and reduce non-uniqueness in Moho imaging.

We processed teleseismic RFs for sixteen broadband stations, including six Estonian sites analyzed for the first time. We extracted the P phases, bandpass filter (0.05–2 Hz), rotate to LQT coordinate system, and deconvolved the seismic data. H–K was applied to estimate Moho depth and V_p/V_s , with resonance corrections for stations on thick sediments (Yu et al. 2015; Zhu & Kanamori 2000). Gravity inversion was carried out on terrain- and sediment-corrected Bouguer anomalies from WGM2012 gravity model, resampled to a 0.1° grid. We employed a tesseroïd-based forward model with Bott's approximation and Tikhonov regularization, and optimized parameters (μ , z_{ref} , ρ) through cross-validation (Uieda & Barbosa 2016). Inversion was constrained using deep seismic transect (DSS) and receiver function data.

RF results show Moho depths from ~35.5 km (SLIT) to ~55.7 km (PA82), with V_p/V_s of 1.70–1.86. Gravity inversion yields smoother values of ~44–49 km, with best-fit parameters $\mu = 1.5 \times 10^{-4}$, $z_{ref} = 47$ km, and $\rho = 700$ kg/m³. Comparison reveals a small mean bias (~0.06 km) but larger scatter ($\sigma \approx 4.3$ km). Local discrepancies between methods reach ~11 km, particularly above the Kurzeme Batholith and in western Estonia. Residuals remain low ($\sigma \approx 0.45$ mGal), confirming that the two-layer model reproduces most of the anomaly power.

Our integrated model refines the Moho map of the Baltic States and highlights the limitations of gravity-only approaches in regions of strong crustal heterogeneity. We emphasize the value of combining RF and gravity methods to resolve lithospheric structure and recommend targeted DSS transects and joint 3D inversion to address remaining complexities. We also highlight the uncertainty of using potential field data for delineation of Proterozoic domain boundaries, urging for more in-depth geophysical studies in the region.

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P7.5

Coupled dissolution-reprecipitation of titanite in the Mesoproterozoic Kabeliai granites in SE Lithuania

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The Mesoproterozoic Kabeliai granites in southern Lithuania (East European Craton) represent an evolved anorogenic intrusion related to ca. 1.5 Ga magmatism. These include microcline granites, plagiogranites, cut by quartz-carbonate veinlets. Alteration of accessory minerals provides insights into the post-magmatic evolution. Samples from the Marcinkonys-7 drill core were studied by SEM-EDS, EPMA, Raman, LA-ICPMS to reconstruct the alteration history.

Titanite grains (50 µm-4.5 mm) are mostly associated with mafic minerals, show clear zoning with Al increasing and Fe decreasing toward the rims. The calculated Fe/Al ratios distinguish magmatic cores (~1.0-0.5) from altered rims (~0.2-0.3), according to the discrimination diagram of Kowallis et al. (2022). Two REE-related trends were identified. Euhedral titanite with porous rims near anatase and hematite shows REE depletion at the rims (e.g., Ce₂O₃: core 0.48-0.56 wt.%, rim 0.10-0.21 wt.%; Nd₂O₃: core 0.20-0.40 wt.%, rim 0.03-0.04 wt.%), with REE-carbonates nearby, suggesting removal and external precipitation. In contrast, anhedral grains show higher REE and F contents at the rims (e.g., La₂O₃ up to 1.27 wt.%; F up to 1.81 wt.%) without REE-carbonates nearby, indicating in situ recrystallisation. Altered titanite is frequently associated with chlorite, epidote, and secondary muscovite.

Two Kabeliai granite samples were analysed at Trinity College Dublin. Concordant grains yield 1520.2 ± 3.6 Ma (MSWD = 0.86, n = 67), while discordant grains define a lower intercept at 1500.5 ± 4.4 Ma (MSWD = 2.1, n = 179), attributed to minor Pb-loss. In addition, titanites analysed at Lund University, Sweden, yielded 1519 ± 5 Ma (unaltered) and 1479 ± 15 Ma (altered), the latter matching an Re-Os molybdenite age (1486 ± 5 Ma; Stein et al. 1998). These ages support syn-magmatic crystallisation followed by fluid-driven alteration. Pseudomorphic replacement of pristine titanite by porous, low-REE rims, along with hematite and anatase formation, reflects coupled dissolution-reprecipitation under oxidising conditions and Fe mobility. The anhedral titanite REE-F enrichment at the rims suggests titanite recrystallisation in the presence of F-bearing fluids, likely sourced from biotite during chloritization. Alteration zones with calcite, hematite, epidote multi-stage albitisation, oxidation, REE redistribution. Titanite thus captures magmatic, fluid-mediated overprint, capturing redox, chemical shifts that shaped the late-stage REE-, Fe-bearing mineral assemblages in the Mesoproterozoic granite.

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P7.6

Tracing magma evolution in the gabbro-norite–anorthosite Sejny Intrusion (NE Poland): geochemical and isotopic insights

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The gabbro-norite–anorthosite Sejny Intrusion, concealed under ~600 m of sedimentary rocks, belongs to the AMCG (anorthosite–mangerite–charnockite–granitoid) Mazury Complex (NE Poland). The zircon U–Pb data reveal its emplacement into Paleoproterozoic country rock between 1513 ± 2 Ma and 1499 ± 3 Ma.

The Sejny anorthosite is characterized by orthopyroxene with abundant lamellae of exsolved plagioclase, which indicates originally high-Al features (5.9–6.7 wt% Al_2O_3) and provides evidence for a deep-seated fractionation, followed by the emplacement of plagioclase-dominated mush into the shallow crust (Chen et al. 2015). The Al-in-orthopyroxene geobarometry (Emslie et al. 1994) indicates the high-alumina orthopyroxene (HAOM) and associated plagioclase crystallized at pressures of 10.3 kbar (~35 km). Dykes of primitive jotunite, with relatively high SiO_2 and low Fe–Ti–P contents, display chilled margins and preserve the composition of the parental magma. Evolved jotunite, enriched in Fe–Ti–P and depleted in SiO_2 , represents residual melts after plagioclase and HAOM fractionation.

The rare earth element patterns and isotopic signatures of primitive jotunite ($\epsilon_{\text{Nd}(t)}$ of –1.6 to –1.8, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ of 0.7040–0.7044, and maximum single $\epsilon_{\text{Hf}(t)}$ of 2.3 (mean = –2.5)) suggest a lower crustal origin. Anorthosite and gabbro ($\epsilon_{\text{Nd}(t)}$ of –1.4 to –2.0, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)}$ of 0.7041–0.7049, mean $\epsilon_{\text{Hf}(t)}$ of –2.2 to –3.6) overlap isotopically with primitive jotunite. In contrast, evolved quartz jotunite ($\epsilon_{\text{Nd}(t)} = -2.4$, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7053$, mean $\epsilon_{\text{Hf}(t)} = -4.1$), quartz gabbro-norite ($\epsilon_{\text{Nd}(t)} = -2.5$, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7043$), and quartz norite ($\epsilon_{\text{Nd}(t)} = -2.7$, $^{87}\text{Sr}/^{86}\text{Sr}_{(i)} = 0.7072$, mean $\epsilon_{\text{Hf}(t)} = -5.5$ and –7.5) show a gradual decrease in ϵ_{Nd} and ϵ_{Hf} , and mostly higher $^{87}\text{Sr}/^{86}\text{Sr}$ values. This is consistent with zircon O–Hf trends for quartz jotunite and quartz norite ($\delta^{18}\text{O} = 6.8\text{--}10.2\text{‰}$, $\epsilon_{\text{Hf}(t)} = -0.4$ to –10.1), reflecting progressive contamination of a juvenile magma by a high $\delta^{18}\text{O}$, low ϵ_{Hf} supracrustal component during its ascent to mid-crustal levels.

Based on its coeval relationship with A-type granitoids of the Mazury Complex, the Sejny Intrusion is interpreted as anorogenic, having been emplaced into stable continental crust some 300 Myr after the last orogenic event. The heat input for the melting might have come from asthenospheric upwelling, likely triggered by heat accumulation beneath the Columbia supercontinent.

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P7.7

Sulfide-bearing nelsonite: a hidden treasure of the Suwałki Anorthosite Massif (Mazury Complex, NE Poland)

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Nelsonites, generally associated with massif-type anorthosites, are Fe-Ti oxide–apatite rocks. They are economically significant as a potential source of Ti and rare earth elements (REE). The origin of nelsonite remains debated and may involve fractional crystallization, oxide–apatite accumulation, silicate–oxide immiscibility, or late-stage metasomatism.

Nelsonite from the Łopuchowo IG-1 drill core (Krzemiński et al. 1988; Wiszniewska 1997) occurs at the western margin of the ~1.5 Ga Suwałki Anorthosite Massif, a part of the anorthosite–monzonite–charnockite–granite (AMCG) Mazury Complex in northeastern Poland. The fine-grained Łopuchowo nelsonite forms several veins within the anorthosite and norite at depths exceeding 2100 m. It contains fluoroapatite (~70 vol.%), Fe–Ti oxides (12–15 vol.%), and unusually abundant sulfides (10–14 vol.%), including Ni-bearing pyrite, chalcopyrite, pyrrhotite, millerite, and sphalerite.

Whole-rock geochemistry reveals variable but exceptionally high total REE contents (1205–7702 ppm), placing the Łopuchowo nelsonite among the most REE-rich examples worldwide. The high REE content is controlled by zoned apatite, with REE-rich cores (0.93–1.72 wt.% REE₂O₃) and REE-depleted rims (0.54–1.06 wt.% REE₂O₃), as well as minor secondary rhabdophane. The high sulfide content of the Łopuchowo nelsonite results in pronounced enrichment in Ni (755–2467 ppm), Co (67–225 ppm), Zn (79–212 ppm), and Cu (931–3332 ppm). The rock shows elevated concentrations of Au (25–70 ppb), Ag (149–507 ppb), and platinum-group elements (PGE), particularly Re (7–28 ppb) and Pd (25–35 ppb). Fe–Ti oxides contribute to elevated Cr (693–1999 ppm) and V (194–622 ppm). Magnetite exsolutions in ilmenite yield crystallization temperatures of 747–887 °C. The presence of zoned apatite and secondary rhabdophane rims over sulfides indicates REE leaching under hydrothermal conditions of ~300 °C. A positive correlation between Ca and S in rhabdophane suggests its precipitation from oxidized SO₄²⁻ rich hydrothermal fluids (Laurent et al. 2016).

The Łopuchowo occurrence represents a rare example of sulfide-rich nelsonites with extremely high REE contents and enrichment in PGE. It reflects a complex crystallization history influenced by magmatic and hydrothermal processes and provides new insights into nelsonite petrogenesis and its potential as a source of critical raw materials.

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P7.8

Magmatic pulses and shear-controlled emplacement of LCT-pegmatites in Bergby, central Sweden: Evidence from field observations and U–Pb SIMS geochronology

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In Sweden, all known granitic pegmatites of the LCT family occur in the Svecokarelian orogen and the Bergby LCT-pegmatite field is the most recent discovery of these types of mineralizations. It is located within the Ljusdal lithotectonic unit in the central part of the country. For the pegmatite dykes at Bergby, it appears that melt accumulation, transport and emplacement were facilitated by ductile and brittle shear, as it has been suggested for similar fractionated pegmatites elsewhere (Holmes & Grigson 2019).

Bergby Li-pegmatite field occurs in refolded metasedimentary rocks, metamorphosed under LP amphibolite facies and thrust onto metagranitoids of the Ljusdal Batholith to the west. Four ductile deformation events produced west-verging folds and thrusts, later open reclined folds, and km-scale shear zones along fold limbs (Högdahl & Bergman 2020). One of them being the Hagsta Gneiss Zone with a documenting shear activity at 1.81 Ga. In the area, there are different types of post-peak metamorphic intrusive rocks represented by gabbro, quartz monzodiorite, amphibole-biotite granite, two-mica granite, barren granitic pegmatites, in addition to the LCT-pegmatites. Pegmatite dykes and a gabbro intrusion within shear zones accommodated some of the strain, suggesting syn- to late-tectonic emplacement, whereas relative ages of intrusions outside the zones remain unconstrained.

To constrain magmatic relationships of these intrusive rocks, U-Pb SIMS analyses were performed on zircon and/or monazite. The simple pegmatite and two-mica granite yielded monazite ages of 1804 ± 3 and 1805 ± 8 Ma. Zircons from LCT pegmatites show severe Pb loss, but a few concordant analyses suggest an age of c. 1.79 Ga. These results indicate a genetic relationship among these lithologies. In contrast, the quartz monzodiorite (1702 ± 1 Ma) and amphibole-biotite granite (1696 ± 5 Ma) represent a younger, unrelated magmatic pulse.

The Bergby pegmatite dykes, including Li-bearing ones, emplaced within shear zones show a ductile kinematic fabric. This feature, along with their crystallization ages, reinforces the link between shear deformation, magma transport and structural trapping.

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P7.9

Geophysical, geochemical, and geochronological characterization of the Märjamaa rapakivi granite in Estonia

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Rapakivi granitoids, defined as A-type granites, which formed due to bimodal intraplate magmatism (Chappell 1974; Clarke 1992), are key components of Anorthosite-Rapakivi Granite Complexes (ARGCs) across Laurentia and Baltica cratons (Rämö & Haapala 1995). In Fennoscandia, ARGCs represent intraplate post-orogenic systems which formed between 1.65 and 1.50 Ga (Åhäll & Connelly 1998; Ashwal & Bybee 2017). The most prominent rapakivi intrusions in Estonia include the Riga batholith and its smaller counterparts like Märjamaa, Naissaare, and Neeme. This study focuses on the Märjamaa rapakivi massif and its satellite Kloostri, the first of which has a highly magnetic centre.

The purpose of this is to update the evolving model of the granites by integrating geophysical, geochemical, and geochronological data to deepen the understanding of Fennoscandian ARGCs (Anorthosite-Rapakivi Granite Complexes).

The MAGMAP tool in Geosoft Oasis Montaj was used to map out various geophysical anomalies with the help of derivative methods. Existing gravimetric and magnetometric data were used for this. Geochemical data from Kivisilla (1999) major elemental compositions; in addition to new ICP-MS data, that were used to assess the petrogenesis, tectonic setting, and magmatic processes in the Märjamaa massif and its satellite. Geochronological data from Rämö et al. (1995), together with two new U-Pb zircon dating analyses, were used to correlate magmatic evolution within the massif and in the context of the wider Fennoscandian area.

The integrated geophysical, geochemical, and geochronological analysis of the Märjamaa intrusion and its satellite, Kloostri classify them as predominantly ferroan, metaluminous A-type granites, and reveals a three-part emplacement sequence along reactivated shear zones. The results highlight strong parallels with Finnish rapakivi granites, demonstrating their shared petrogenetic evolution. These findings contribute to a more detailed model of Estonian anorogenic intrusions and outlines prospective zones for ore exploration.

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P7.10

Staicele and Gārsene Proterozoic iron ore deposits of Latvia: mineralogical, chemical features, and genesis

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The crystalline basement of Latvia was formed 2–1.75 billion years ago during the Svecofennian orogeny, when merging of numerous microcontinents and island arcs led to the formation of the supercontinent Columbia/Nuna (Bogdanova et al. 2015). Several magnetic and gravitational anomalies caused by iron ore deposits were discovered in 1920s and later in the part of the Latvian-East Lithuanian block crossing the territory of Latvia. The most of mineralogical, petrographic, geophysical, and geochemical studies of Latvia's Proterozoic iron-bearing rocks were conducted in the 1980s–1990s (e.g., Vetrennikov 1984) and then ceased. The available data on the Staicele and Gārsene deposits are outdated. The processes of iron accumulation and concentration, as well as the effects of metamorphism and other ore-altering processes, remain poorly understood and require further study.

This research presents new data on two main iron ore deposits of Latvia — Staicele and Gārsene — using macrosample and thin-section studies and analytic methods such as SEM-EDX, XRF, XRD, and ICP-MS. For these purposes, 44 ore samples from the Staicele-1 drill cores (Staicele deposit) and 24 samples from the Subate-2A drill cores (Gārsene deposit) were selected, classified, and studied. The new results allow to clarify the chemical and mineralogical composition of the ores and provided new insights into their formation.

According to this study, these two deposits are classified as banded iron formations (BIF) of the Algoma (Staicele) and Lake Superior (Gārsene) types. This conclusion is based by the presence of europium anomalies in Staicele and their absence in Gārsene ores, REE fractionation, and the presence of terrigenous components in both cases. At the same time, the ores of the Staicele deposit have an increased manganese content in both silicate (up to 22.1 wt% MnO) and oxide minerals. In Gārsene, elevated concentrations of vanadium and titanium are also observed in the amphibole-magnetite quartzites, while the content of cobalt is increased in the magnetite quartzites associated with sulfide (pyrrhotite-pyrite) mineralization. Staicele ores are notable for high manganese content, mostly related to such silicates as garnets and pyroxenes, but also to magnetite (3.1 wt% MnO in average) forming magnetite-jacobsite series.

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O8.1 (Keynote)

Carbon mineralization in Iceland – challenges and opportunities in large-scale deployment

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The Carbfix technology has been demonstrated as a safe and cost-effective approach to permanently store carbon dioxide (CO₂). Unlike conventional carbon capture and storage (CCS), this methodology relies on CO₂ solubility and mineral trapping within basaltic formations mimicking the natural process of chemical weathering of silicate minerals. It involves dissolving CO₂ captured from point sources or air in water and injecting this CO₂-charged water into storage reservoirs. Since the CO₂ is dissolved in water, it is no longer buoyant and thus has no tendency to migrate back to the surface. The enhanced dissolution of the basaltic rock in the storage reservoir liberates divalent cations from the host rock which become available for precipitation of carbonate minerals.

Since 2012, Carbfix has injected over 100,000 tonnes of CO₂ at several sites. The current focus is on further scaling up the technology and assessing its engineering and geological limits for broader deployment. The EU-funded Coda Terminal project, which has been under development since 2020 in Iceland, represents a significant step towards large scale implementation of CO₂ mineral storage, with the planned capacity of storing up to 3 MtCO₂/yr when reaching full scale of operations.

Despite the positive results from feasibility studies carried out at the originally proposed injection site in Straumsvík in the Hafnarfjörður municipality, the project encountered strong opposition from the local community. The primary concern centered around the close proximity of the injection site to the residential area. Although Carbfix has been operating CO₂ injection sites since 2012, the public perception of the technology is still regarded as new. Specific concerns such as seismicity, groundwater contamination, salinity and water level change, were addressed in the EIA and resulted in a positive conclusion by the National Planning Agency.

The experience highlights the critical importance of early, transparent, and sustained stakeholder engagement, especially in the early stages of project development. Building trust requires adequate time and resources, especially as the laws and regulations regarding the complete cross-border CCS value chain are still in their early stages and the first projects will be pioneering projects in this aspect. Furthermore, educating the local communities on CO₂ storage technologies and visible support from the local and national political representatives is crucial for successful implementation and acceptance of climate mitigation solutions at scale. In this regard, recent support for CCS by the Icelandic government - namely including CCS from local ETS-industries among the 5 top priority climate actions, is a positive development. Similarly, CCS was recently included in draft plans of Iceland's Nationally Determined Contributions (NDC) to the Paris Agreement by the Minister of the Environment, Energy and Climate.

08.2

Fracture-controlled multi-stage secondary mineralisation and alteration in Kaldakvísl basaltic lava group, Husavík–Tjörnes Peninsula, NW Iceland: implications for CO₂ storage

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Recent pilot projects, e.g. CarbFix and Wallula, where CO₂ have been successfully injected into subsurface basaltic rocks and converted to carbonate minerals within a few years, highlight the advantages of *unconventional reservoirs* (mafic and ultramafic rocks) for long-term, safe CO₂ storage. Despite the advantages, the CO₂ storage potential in unconventional reservoirs is relatively underexplored. Consequently, the key factors (and/or their interplay) impacting secondary mineralisation and the storage capacity of basaltic lava flows in the subsurface are less well understood. Here, we integrate field observations with petrographic-, geochemical-, and SEM- analysis, to characterise Miocene age Kaldakvísl basaltic lava flows, and deformational structures exposed along the western and eastern coast of the Husavík–Tjörnes Peninsula, NW Iceland. Our results reveal at least two phases of fault activities and vein development, linked with deformation on a major oblique-slip fault, the Husavík-Flatey Fault Zone (HFFZ), located south of the western coast. The lava flows were largely characterized by tabular geometries, variable thicknesses (c. 1 – 7 m), and sometimes interbedded with thin volcanoclastics and paleosols. Individual lava flows exhibited large variability in intra-flow vesicle intensity, connectivity, and mineral fill, allowing us to subdivide each flow sequence into three units; base-, core-, and top- of flow. Field observations and geochemical analysis of lava flow sequences from the western coast show that the flow tops have been subjected to intense and higher degrees of hydrothermal alteration and secondary mineralisation (e.g. zeolites and minor carbonates) compared to the flow base and core. Conversely, lava flow sequences from the eastern coast, with less deformation, are generally less altered, preserving the original composition (no zeolites) and open vesicles of the lava flows. This suggests a strong correlation between the degree of deformation and tectonic fracturing, and the degree of hydrothermal alteration and secondary mineralisation observed in the western vs. eastern coast. Furthermore, the result of XRD analysis identified zeolite minerals that formed both at lower temperatures (55–110°C), e.g., chabazite and natrolite, and higher temperatures (70–300°C), e.g., stilbite and analcime. We propose that these zeolites form from distinct hydrothermal alteration events, reflecting a multi-stage rather than a continuous mineralisation and alteration process. Our observations suggest that the multi-stage alteration process was most likely driven by the multiple phases of fault activities and vein formation associated with the HFFZ and subsidiary faults. This study improves our understanding of the factors influencing hydrothermal alteration and secondary mineralisation in basaltic rocks, and has implications for evaluating the interplay between the development of fractures and CO₂ storage potential in unconventional reservoirs.

O8.3

Petrographical and petrophysical analyses of potential CO₂ storage complexes in the Faroe Islands Basalt Group, Faroe Islands NE Atlantic Ocean

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Interest in Carbon Capture and Storage (CCS) within volcanic settings has during the last decades increased due to basalts ability to rapid sequester carbon dioxide to form carbonates. This study investigates the carbon storage characteristics of two epi-volcaniclastic units (Argir and Sund beds) drilled by the onshore well Glyvursnes-1 into the Faroe Islands Basalt Group (FIBG) in the Faroes Islands, NE Atlantic Ocean, which is part of the Palaeogene North Atlantic igneous province. From the acquired wire-line suite, the reliability of wire-line derived porosities is examined. We show the relationship between the density log derived porosity, the ImageJ analysed macroporosity, conventional core measurement and present a model in which both the range in ImageJ and core measurements can be predicted based on wire-line logs and thereby greatly improves the reservoir evaluation. The macroporosity and measured permeability within the investigated units showed averages of 4.7% and 5 mD and medians of 3.8% and 1.9 mD, indicating that the units may play several roles in potential carbon storage sites in the FIBG. The model has been tested using drilled intervals from wells located on- and offshore Faroe Islands (Faro-Shetland Basin) and suggests that the FIBG offers a possibility for CCS in the NE-Atlantic region and similar volcanic areas.

O8.4

Fluid connectivity and evolution of pore water in breakup basalt offshore mid-Norway with implications for CO₂ storage

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Basalt complexes can cover thousands of square kilometres and be several kilometres thick. With an estimated global carbon storage capacity of 40 Tt they represent a possible solution to reach the 2050 emission targets. However, the injection of gigatons of CO₂ into basaltic formations requires a thick reservoir system lacking barriers to lateral fluid flow for the CO₂ to dissipate away from injection points. In this contribution, we evaluate for the first time the vertical fluid connectivity of a basalt sequence using the Sr isotope composition of pore waters, sampled using the strontium residual salt analysis (SrRSA) method. Thirty-seven samples were collected in the U1571A borehole (IODP Expedition 396 on the Skoll High, offshore mid-Norway). Sampling of the well targeted the most representative lithologies and hence included vesicular basalt and massive flow interiors.

The SrRSA method measures the ⁸⁷Sr/⁸⁶Sr ratio in the salt residue that precipitated in the pores of core samples after the pore water evaporated, and the value measured in the laboratory should accurately reflect that of the in-situ pore water. In addition to present-day pore water from the residual salts, the ⁸⁷Sr/⁸⁶Sr of past water compositions were reconstructed from carbonate cements of different ages. We reveal smooth and uninterrupted trends in strontium isotopes through a 100 m thick basalt section indicating a common fluid reservoir unaffected by the low-permeability massive lava flow interiors. The data further indicate that the unconsolidated overburden sediments act as a good seal preventing seawater to mix with in situ porewater and may prevent CO₂ leakage to the surface for buoyant supercritical CO₂ injection scenarios. This study supports the premise that basaltic sequences form viable targets for CO₂ storage and suggests that fractures may bypass low-permeability units to create a well-connected reservoir system. Finally, the ⁸⁷Sr/⁸⁶Sr method is demonstrably useful in basalts, and warrants being included routinely in evaluating thick basalt sequences for large-scale CO₂ storage.

08.5

Paleogene Evolution of the Vøring Transform Margin: A Tectonostratigraphic Study of the Mimir High Using Seismic and Borehole Data

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Transform continental margins account for 16% of global continental margins however only few have been drilled, which limits our understanding of their evolution. The Mimir High, a prominent structural high situated along the Vøring Transform Margin (VTM) offshore Mid-Norway, represents a key location for addressing this knowledge gap. It was drilled in 2021 during International Ocean Discovery Program (IODP) Expedition 396, providing the first direct access to borehole samples from this part of the margin.

This study aims to refine the tectonostratigraphic evolution of the Mimir High through integration of newly acquired high-resolution 3D P-Cable seismic data from the 2020 CAGE20-4 cruise and five boreholes at sites U1569 and U1570. Methods include seismic horizon and attribute interpretation, wireline log analysis, and core-log-seismic integration supported by biostratigraphic data.

During the Paleocene-Eocene Thermal Maximum (PETM), around 55.9 million years ago, as dated by the presence of the dinocyst *Apectodinium augustum*, the area was characterized by a clastic shallow marine environment, likely lagoonal in nature. The ash-rich mud- and siltstones indicate ongoing volcanic activity in the vicinity. A notable early Eocene volcanic event is recorded in the form of a 10-meter-thick dacitic igneous unit, interpreted as a subaqueous pyroclastic density current.

Post-PETM, early Eocene sequences show signs of uplift and truncation, forming an angular unconformity that is likely related to thermal uplift from the nearby seafloor spreading axis. These sediments represent a coastal, ash-rich clastic system with substantial terrestrial input. The Mimir High remained subaerial or coastal until submersion during the late Oligocene. In the early Miocene, regional uplift, linked to a broader inversion event, was followed by subsidence. Miocene and younger sequences record marine transgression and deposition of sand-rich mudstones.

This study presents a new seismic interpretation, refined chronological and paleoenvironmental constraints, and enhanced insights into the evolutionary development of the VTM and the associated Mimir structural high. These results will be further integrated in the near future into a regional tectonic scale and modelling of shallow and deeper processes caused by breakup related mechanisms.

O8.6

Crystal Clear: A Petrophysical Databank of Crystalline Rocks for Assessing Deep Geothermal Reservoirs in Fault Zones

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As part of the Deep-HEAT-Flows project, we have compiled a large databank of crystalline rocks transected by faults to evaluate their petrophysical variability and geothermal potential. Over 1500 samples from outcrops and boreholes up to 2 km depth were collected; ~500 were analyzed for density, elastic wave velocity, porosity, thermal conductivity, heat capacity, electrical resistivity, and magnetic susceptibility. Gas permeability was measured on ~100 samples at 1 MPa, with ~30 further tested up to 50 MPa. Complementary petrography, XCT, μ -XRF, SEM-EDS, and U–Pb dating provided insights into mineralogy, pore morphology, and the timing of reservoir formation. Results reveal a clear correlation between fault architecture and petrophysical properties. Massive rocks typically are located at the host blocks of faults, showing porosity <2% and permeability below 10^{-17} m², whereas brecciated and altered rocks in fault cores reach porosities >30% and permeabilities up to 10^{-11} m². In altered rocks, XCT scans indicate pore connectivity of 60–96%, linked to feldspar and quartz dissolution and replacement of mafic minerals by chlorite and epidote. Permeability in altered and brecciated rocks remains high under confining pressures equivalent to ~2 km depth, in contrast to fracture-dominated rocks where permeability rapidly declines. U–Pb dating of secondary titanite in one area constrains porosity development to Proterozoic tectono-hydrothermal events (2200–1750 Ma), indicating that reservoir-quality properties are largely inherited from ancient crustal processes. Numerical thermal–hydraulic modeling of a 3.5 km-deep doublet EGS exploiting such reservoirs predicts stable outputs of 2.9–3.3 MW_{th} over 50 years, with minimal thermal breakthrough. These results demonstrate that crystalline shields, long considered unfavorable, can host naturally permeable reservoirs capable of sustaining MW-scale geothermal production. The dataset establishes predictive relationships between fault architecture, alteration, and reservoir properties, offering a framework for geothermal exploration in crystalline cratons globally. This work challenges conventional assumptions, showing that fault-hosted crystalline reservoirs at modest depths are viable for district heating and industrial use in markets like in northern Europe. In addition, their natural permeability and alteration signatures provide opportunities for soft hydraulic stimulation and potential co-production of strategic elements from geothermal fluids. Overall, the Crystal Clear databank underscores that Precambrian shields represent untapped resources for sustainable geothermal energy, offering a predictive framework for identifying fault-hosted reservoirs and supporting future MW-scale developments in crystalline settings.

08.7

The interplay of brittle deformation and mineral alteration in the genesis of crystalline reservoirs, Southern Finland

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Achieving large-scale geothermal energy production in Finland requires an extensive understanding of the processes that enhance fluid and heat flow within crystalline rocks. Fault zones can act as conduits, with permeability being greater at damage zones with higher fracture connectivity (Bense et al. 2013). Nevertheless, other processes such as mineral alteration are likely necessary to enhance permeability within crystalline rocks and consequently improve the outcome of geothermal boreholes (Bischoff et al. 2024).

This study focuses on the interplay between brittle deformation processes and mineral alteration that can create crystalline reservoirs in Southern Finland. We use field and drone-based mapping, and topological and petrographic analyses to characterize fracture zones in the crystalline granitic rocks of Turku, Southwestern Finland. With this, we aim to highlight how mineral alteration, and fracturing can form highly porous and permeable crystalline rocks.

Our results reveal the co-existence of five main fault sets with strike-slip kinematics, trending: 1) N-S; 2) NE-SW; 3) E-W; 4) NW-SE; 5) ENE-WSW. Sets 1, 2 and 4 have sinistral kinematics, while sets 3 and 5 have dextral. All sets were found within the damage zones of >10 km long faults and shear zones. The set 2 faults abut against and crosscut set 1 faults, while set 3 faults abut against and crosscut set 1 and 2 faults. The crosscutting relationship of set 4 and 5 is unclear. Higher degree of mineral alteration correlates with increased brittle deformation. Sericitization is the dominant alteration followed by chloritization, quartz precipitation and garnet dissolution. The average porosity in relation to fault zones is 4 %, reaching up to 18 %, and a permeability of $\sim 3 \times 10^{-12} \text{ m}^2$, primarily due to mineral alteration. Higher degree of brittle deformation in set 5 faults and crosscutting set 1 and 3 fault zones preferentially channelled hydrothermal fluids along damage zones, which in turn triggered intense mineral alteration and enhanced permeability. Our study will increase the understanding of which brittle structures have undergone a permeability enhancing mineral alteration. This will allow to correlate our findings to a regional structural context and improve geothermal prospectivity.

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O8.8

Multi-Scale Constraints on Geothermal Reservoir Formation in Crystalline Basement: Kivetty Site, Finland

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The potential for geothermal resources in crystalline shields is usually limited due to low geothermal gradients and low matrix porosity and permeability. The Kivetty site in central Finland offers a rare natural laboratory: 13 deep boreholes into the ~1.88 Ga granodioritic basement yield a unique core dataset for assessing fault-zone geothermal potential. We combined gas porosity and permeability measurements, micro-XRF elemental mapping with automated mineral classification (AMICS), high-resolution X-ray computed tomography with fluid-inclusion microthermometry to constrain reactive-transport simulations. Petrophysical measurements documents altered intervals reach porosities up to 30%, pore connectivity above 90%, and permeabilities up to 10^{-12} m², sustained under confining pressures equivalent to ~2 km depth. Long-term cross-well pumping tests show hydraulic connections between wells up to 1.5 km apart, confirming large-scale connectivity across faulted zones without stimulation. Fluid inclusions yield trapping temperatures of 70–345 °C and 7–20 wt% Na–Cl salinities, providing point constraints of hydrothermal alteration. Simulations, constrained by these measurements, reproduce the observed dissolution of biotite, K-feldspar, albite, and quartz and the precipitation of chlorite, muscovite, epidote, iron oxides, and clay minerals, generating highly connected pore networks within fractured crystalline rock. Local bastnäsite (REE fluorocarbonate) occurs within altered zones. This multi-scale observations and simulations shows how hydrothermal fluids can generate and preserve natural permeability in crystalline basement, explaining why some shield faults behave as porous, permeable geothermal reservoirs in non-volcanic regions. The results are relevant for assessing geothermal prospects and the co-recovery of critical elements (eg., Li, He, H₂) from geothermal water for the energy transition.

08.9

Critical raw materials from thermal fluids: origin, extraction, demonstration

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The extraction of critical raw materials (CRMs), such as lithium, helium, strontium, or rare earth elements, from deep fluids is currently being investigated in many geothermal areas worldwide. The occurrence of CRMs and their extraction technologies are highly site-specific, and the economic feasibility of co-extracting heat and CRMs has so far been poorly demonstrated.

In general, geological conditions determine the composition of geothermal fluids, while the efficiency of extraction technologies depends on the brine composition and the plant conditions. The EU-funded project "CRM-Geothermal" pursues a holistic approach to the evaluation and extraction of critical raw materials from geothermal fluids in Europe and East Africa.

Its objectives are as follows: (I) To assess the overall potential, a database will be established, and the collected fluid data will be visualized in a fluid atlas. (II) The origin and mobilization of CRMs will be investigated for different geological settings (e.g., in crystalline, fractured rock or in deep sedimentary basins where high-salinity waters circulate through porous formations) in order to make predictions about the occurrence and sustainability of extraction during fluid circulation. (III) Innovative extraction technologies will be developed for some CRMs, such as lithium, strontium, and helium, for different fluid types. Furthermore, economic, social, and environmental aspects of the processes will be considered, and finally (V) the feasibility of CRM co-extraction will be demonstrated at a site (Cornwall).

08.10

Carbonation and hydrothermal alteration of volcanic rocks in the Oslo Rift

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The Oslo Rift formed around 300 million years ago and is characterized by emplacement of subaerial lavas and an extensive subvolcanic system of sills, dykes and plutons. The earliest stages of volcanism were dominated by fissure-fed plateau basalts, trachyandesites to trachytes (including rhomb porphyries), followed by later stage caldera-related basalts, rhyolites and ignimbrites. More than 1.5 km of rhomb porphyry stratigraphy is preserved in the ca. 250 km long subaerially exposed rift system, but primary igneous minerals are often completely altered, except for apatite and rare zircons. Interestingly, the sedimentary rocks forming the substrate for lavas remain unaffected by hydrothermal alteration, questioning conventional models for fluid flow and temperature evolution in rifts.

Here, we use new boreholes and cores from the Oslo Rift to characterize and further understand rift-scale pervasive alteration of lava flows. We focus on two cores. The first core includes 350 m of interbedded sandstones and lava flows, and the second one is 50 m long and drilled through a fault zone in the two lowermost flow units. We present wireline logs, geochemical data and petrography to further understand the hydrothermal alteration and porosity-evolution in these rocks. Overall, primary igneous minerals (e.g., pyroxene, ternary feldspar, ilmenite) were hydrated and replaced by mineral assemblages including chlorite, albite, K-feldspar, quartz, calcite, rutile, monazite and magnetite. Vesicle-rich horizons in the lavas (flow bases and tops) are filled by chlorite and calcite, with minor dolomite, quartz, epidote, fluorite, barite and pyrobitumen. Vein minerals include calcite, quartz and epidote. We present the carbon and oxygen isotope systematics of carbonates, and Raman-based geothermometry of pyrobitumen. Our results shed light on the complex history of fluid-rock interactions in a continental rift. Lavas acted as reactive lids, trapping water and light and mobile elements such as carbon and alkalis, whereas apatite-hosted REE still preserve igneous geochemical signatures. Hydrothermal circulation took place across a large temperature range, with maximum temperatures (ca. 260-300 °C) recorded by quartz plus epidote assemblages and pyrobitumen. Conceptual models need to include the variability of fluid sources during rift progression, including igneous/mantle, contact metamorphic, basinal brines, meteoric and possibly seawater sources.

08.11

Mercury and silver release during contact metamorphism of shale

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Elevated mercury (Hg) in sedimentary strata are a widely used tracer for assessing the relationship between large igneous province (LIP) activity and global environmental change. A key unknown in applying this proxy is the extent to which Hg was sourced from gaseous emissions by magmas or contact metamorphism of sedimentary rocks during sill emplacement. Here we investigate the Hg and silver (Ag) behavior during contact metamorphism of shales. We show loss of 80–99% of the sedimentary organic-bound Hg in contact aureoles in four case studies covering the interactions around dykes, sills, and plutons associated the High Arctic LIP (Sverdrup Basin, Canada), the Karoo LIP (South Africa) and the Skagerrak-centered LIP (Oslo Rift, Norway). A combination of geochemical data and thermal modelling around a Sverdrup Basin dyke shows 33% Hg volatilization in the aureole at 265–300 °C. The other cases show similar trends with significant lowering of organic-bound Hg, particularly in the innermost 60% of the contact aureoles. A small fraction of the Hg remains in the aureoles, and thermal desorption characteristics or ‘profiles’ (TDPs) for Hg during pyrolysis provide insight on sample-level Hg speciation. Our results demonstrate that differences in Hg speciation can be detected and quantified with TDPs. We hypothesize that gaseous Hg is transported out of aureoles during metamorphism, together with CH₄ and CO₂. Analyses of Ag in the same samples shows that Ag is also lowered in the shales during progressive metamorphism, but the pre-metamorphic Ag contents are correlated with the sulfur content. We estimate the thermogenic Hg mobilization from Karoo LIP aureoles as 72–192 t per km³ of aureole, which is between 1–3 times higher than the estimated volumetric Hg release from Karoo magmas. When scaling our results to the size of the shale portions of the Karoo Basin affected by the LIP and a timescale of 100 kyr of sill emplacement, the average Hg flux is calculated to have been 78–207 t per year with maximum values up to ~300 t per year. The pulsed nature of intrusive magmatism suggests that this thermogenic Hg flux could have dominated LIP Hg emissions during intervals when it took place. Our results demonstrate that the global Hg cycle can be significantly perturbed following LIP-scale sill emplacement into organic-rich sedimentary rocks and our quantification of the emissions based on source-rock analysis provides important information for independent interpretation of the sedimentary Hg record. The significance of the aureole Ag changes remains to be detailed.

P8.1

Classification of secondary mineral alteration and degree of porosity of fault and fractures on Åland Island

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Geothermal energy is increasingly sought for its renewable and dual-use potential in electricity and heat production. Within Finland, the rapakivi batholith of Åland is an area with relatively high geothermal energy potential (Arola et al. 2024). However, sufficient permeability is required for water, and subsequently heat, to flow through the crystalline bedrock and it is controlled by the interplay between pore spaces and brittle structures. Higher permeability might be the result of hydrothermal fluid circulation, which induce secondary alteration and cause some minerals to leach, resulting in higher porosity (Bischoff et al. 2024). Brittle structures are pervasive in the area, as shown by prior research (e.g., Nordbäck et al. 2024). However, no studies have investigated secondary mineral alteration or porosity in relation to the structures.

The purpose of this study is to investigate secondary mineral alteration and porosity in Åland, focusing on identifying which areas or rapakivi granite types are most typically associated with these phenomena, and how they relate to brittle structures. Observation localities were selected across different rapakivi types and both near major shear zones (lineaments) and in areas between them. The main emphasis was on road cuts, where the fresh surfaces are exposed and the observed porosity is assumed to better represent the significant rock porosity compared to that caused by surface weathering on outcrops. In total, 15 road cuts were mapped and as a comparison, 9 additional outcrops located near the road cuts were also mapped. A total of 68 samples were collected, of which porosity, density, and magnetic susceptibility were measured from 18 samples. Additionally, 26 samples were prepared as thin sections for petrographic descriptions.

Preliminary results indicate a range of porosity of 0,8-8,2 % in altered samples and a porosity of 1,5-1,8 % in non-altered samples. A comparison between alteration color and rock type show that the highest average porosity (4.2%) occurs in red, altered, even grained rapakivi. Based on these findings, the most porous localities are in the central part of Åland.

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P8.2

Magmas meet hydrocarbons: evidence for magmatic and sedimentary carbon release at Bile Island (Skagerrak LIP)

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The interaction between magmas and organic matter in host sedimentary rocks can drive ore mineralization, hydrocarbon cracking and thermogenic gas emissions. When this interaction occurs in large-scale volcanic basins, it has the potential to perturb the global carbon cycle. We investigated magma–hydrocarbon interaction processes by studying basaltic melts intruding bitumen- and oil-bearing sandstones in a continental rift setting, combining detailed field observations with geochemical analyses, and melt and fluid inclusions observations. Our case study is Bile Island in the Oslo Fjord (Norway), where numerous dykes and a sill formed the shallow plumbing system of a nearby basaltic volcano, part of the ca. 300 Myr-old Skagerrak Large Igneous Province.

We report the occurrence of abundant pyrobitumen within sandstone xenoliths, dolerites and hydrothermal breccias from the sill. Using a multi-technique approach, we characterized the transformation of bitumen and oil into pyrobitumen, accompanied by abundant methane (CH₄) and ethane (C₂H₆) emissions. Geochemical data reveal element exchange and mass transfer between melts, fluids and host rocks, crossing from the magmatic into the hydrothermal stage.

Bile Island preserves an exceptional record of synchronous magmatic and sedimentary carbon release via the same volcanic vent(s), providing a viable mechanism for methane emissions in volcanic areas and offering a new paradigm for degassing in the context of Large Igneous Provinces.

P8.3

Behavior of Coastal Amagmatic Geothermal Systems: Thermal–Hydraulic Modeling Insights from La Jolla Beach, Baja California, Mexico

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Coastal amagmatic geothermal systems are a promising energy resource, yet the processes that localize and sustain their discharge remain unclear. We investigate why one of the hottest known amagmatic coastal systems, La Jolla Beach (NW Baja California, Mexico), discharges ~100 °C mixtures of meteoric water and seawater directly at the shoreline along the crustal-scale Agua Blanca strike-slip fault (ABF). We performed large-scale 3D coupled thermal–hydraulic simulations, calibrated by geological, structural, geochemical, and geophysical observations to reproduce key features: discharge temperature and salinity, the footprint and position of the surface thermal anomaly, and meteoric-water residence times. Calibration favors an ABF damage-zone permeability of 10^{-14} m² and hydraulically active width of ~100 m. With these properties, topography-driven hydraulic head gradients are sufficient to drive deep (> 5 km) meteoric water circulation toward the fault's coastal intersection at La Jolla Beach. The Pacific Ocean acts as an effective hydraulic barrier to offshore migration of the convecting meteoric water, creating a subvertical thermal upflow plume that focuses mixed hot fluids to the shoreline. Coastal sediment cover and basement relief further control the location of the discharge site. Tracer and residence-time analyses indicate that lateral inflow from topographically fractured granitoids supplies about half of the deep fault water flux. This underscores the 3D nature of the flow system and shows that regional fault zones such as the ABF can collect meteoric recharge from large areas, sustaining deep geothermal circulation even in arid settings. These results give insights into the coupled thermal–hydraulic controls on the location and magnitude of coastal amagmatic coastal discharge and provide transferable, testable criteria for exploring geothermal potential in analogous tectonic settings worldwide.

P8.4

Structure, formation and ore-forming implications of hydrothermal vent complexes in sedimentary basins

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Hydrothermal vent complexes are formed in sedimentary basins when magma is intruded into host rocks. More than a thousand vent complexes have been identified on 2D and 3D seismic data in the Vøring and Møre basins offshore mid-Norway. They were formed due to emplacement of mafic sills around 56 million years ago, mainly above the termination of high-amplitude reflections interpreted as sills. The upper part of the vent complexes are dominantly kilometer-sized semi-circular crater- or eye-shaped structures at the top Paleocene level, whereas a pipe-like structure of discontinuous reflections connects the upper part with the sill termination. The vent complexes were likely formed due to heating of sedimentary rocks in metamorphic aureoles surrounding the sills, leading to pressure build-up due to formation of greenhouse gases (methane, carbon dioxide) or boiling of water at shallow levels (< 1-2 km depth). For thick sills, typically 100 m or more, aureole rocks of about half the sill thickness may enter supercritical conditions for water (375 °C and 22 MPa pressure equal to about 2.2 km water depth). The crater of a shallowly buried hydrothermal vent complex was drilled during IODP Expedition 396 at Sites U1567 and U1568, documenting that the crater infill is partly of Paleocene-Eocene Thermal Maximum (PETM) age (c. 56 m.y.). These crater sediments are rich in pristine siliceous microfossils and ash layers, with no clear hydrothermal overprint. A vent complex was previously drilled by industry in the Vøring Basin (6607/12-1) showing that that a sub-set of PETM-age microfossils had a high thermal alteration index (TAI). We have conducted extensive field work in the Karoo Basin, South Africa, and the Tunguska Basin, Siberia, to characterize similar onshore exposure of hydrothermal vent complexes. The ones present in Karoo are dominantly sedimentary structures, filled with mud breccia and remobilized sandstones, with rare basalt fragments. However, the Siberian vent complexes have a strikingly different geology, with abundant iron oxide deposits (magnetite) of the Angara-Ilim type infill the basalt pipes. Some of the satellite pipes do not reach the paleosurface, forming so-called cryptovolanic hydrothermal vent complexes. The vent complexes are well exposed in mines and were extensively cored. World-class Ni-Cu-PGE sulfide deposits are also associated with the Siberian Traps magmatism in the Tunguska Basin and are mined for decades in the Norilsk-Talnakh region. We propose that the extensive ore mineralization in the Tunguska Basin is largely related to the unique sedimentary basin deposits which includes extensive Paleozoic salt deposits (evaporites), carbonates and organic-rich shale and coal sequences, whereas the magma type and emplacement processes are comparable to the non-mineralized Vøring and Karoo basins which are dominated by clastic sedimentary sequences.

P8.5

Geothermal potential of the crystalline basement in Estonia: integrating downhole logging, petrophysics, heat flow density data and hydrogeology

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The crystalline basement of Estonia represents an underexplored geothermal target within the Fennoscandian Shield. While shallow geothermal systems are widely used, the potential of deeper resources for industry or district heating remains uncertain due to limited borehole depths (<800 m), the scarcity of high-quality heat flow estimates, and radiogenic heat production data.

This PhD project addresses these gaps by integrating borehole geophysics, petrophysics, distributed temperature sensing (DTS) monitoring of geothermal wells, and numerical modelling to estimate subsurface temperatures down to depths of 2–8 km in crystalline rocks. Data gathered from recently drilled deep geological mapping boreholes and geothermal boreholes (500–700 m) within the GEOENEST project will form a key part of the analysis.

Building on recent advances in site-specific rock thermal property measurements and geothermal systems modelling (Piipponen et al. 2024) and elevated interest in geothermal energy exploitation regarding the EU green transition plans for integrating it into district heating systems (Zajacs et al. 2025). This study will (1) re-evaluate and expand the Estonian heat flow density database through new or revisited borehole measurements, (2) determine radiogenic heat production of basement rocks using drill core and cuttings, and (3) combine these datasets with crystalline basement structural regions to improve interpolation of heat flow across poorly characterized areas. The results will provide the basis for temperature–depth models, calibrated against available deep boreholes in Estonia and Finland. Beyond conductive processes, groundwater circulation in fractured crystalline rocks may locally modify the thermal regime. An ongoing study will also examine the role and connectivity of major and minor fracture zones (e.g., Ediacaran Gdov vs. weathered zones) and how deep such pathways may extend.

The outcomes will deliver a systematic evaluation of the geothermal potential of Estonia's crystalline basement and contribute to regional assessments across the Fennoscandian Shield. These results aim to support future exploration and attract investment in medium-deep to deep geothermal utilization as part of the green energy transition.

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09.1 (Keynote)

Environmental impact of the 2025 Mw 6.5 Jan Mayen earthquake: A climate-change conditioned rock slope failure on Jan Mayen Island, Arctic Ocean

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Climate change is reshaping natural hazards in polar environments by reducing rock stability in permafrost and deglaciating terrains. Here we present a multidisciplinary investigation of the 10 March 2025 Mw 6.5 Jan Mayen oceanic transform fault earthquake in the Arctic Ocean, with the fault rupturing for ~40 km long and crossing the north zone of the Jan Mayen Island, indicating the potential for local hazard effects. The earthquake triggered the first scientifically observed rock avalanche on the adjacent Jan Mayen Island. Using relocated local seismicity, regional waveform modeling, teleseismic records, Global Navigation Satellite System time series data, seismic noise interferometry, infrasound signals, high-resolution satellite imagery, and local air temperature records, we reveal a sequence of events linking earthquake rupture with cascading slope failure. Our results show that intense ground shaking caused by the earthquake initiated a rock avalanche from a glacier-adjacent volcanic slope with a large volume ($0.81\text{--}1.17 \times 10^6 \text{ m}^3$) of basaltic rock that detached, affecting the Kjerulf Glacier and burying it beneath a debris layer. In addition, the earthquake also triggered calving on Weyprecht Glacier, revealed by satellite data. We interpret this instability as climate-change conditioned: permafrost degradation and warmer summers reduced rock-wall strength, and increased susceptibility to co-seismic failure. No comparable slope failures are evident in the historical earthquake record of the last 40 years. These findings demonstrate that climate change is an emerging amplifier of seismic hazard in Arctic volcanic settings, with implications for hazard assessment across other glacierized and permafrost volcanic regions worldwide.

O9.2

Natural fracture ventilation influencing the behavior of rock slope instabilities

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Networks of open bedrock fractures are a common feature in unstable rock slopes. Such fracture systems influence the subsurface thermal regime by allowing air circulation and water infiltration. Ground temperature conditions are in turn a crucial factor controlling slope stability. Mapping subsurface fracture systems in unstable rock slopes therefore remains one of the biggest challenges in assessing the risk such slopes pose to nearby inhabitants and infrastructure.

The Stampa rock slope (Aurland, Norway) is a complex instability with an estimated total volume exceeding 800 Mm³. Although a collapse of the entire slope is considered unlikely, unstable rock sections along an up to 100 m high rock cliff represent potential sources for partial slope failures. This cliff marks the transition between the scree slope below and the gently sloping mountain plateau above, which hosts morphological depressions, graben structures, and open tension fractures where air flow at vents has been observed. To investigate the underground fracture system, we have systematically mapped vent locations in the field aided by UAV-based optical and thermal imaging. We equipped 11 fracture vents with air temperature loggers, three of them with rock surface temperature loggers, and two of them with sensors to monitor velocity and direction of air flow, as well as radon content. These continuous monitoring data are complemented with occasional in-situ air flow and temperature measurements at fracture vents, in addition to radon (²²²Rn) and thoron (²²⁰Rn) surveys using alpha track detectors.

Our results show that there exist several complex ventilation systems connecting vents at different elevations both on the mountain plateau and in the rock cliff. Chimney ventilation is probably most important and is predominantly controlled by the outside air temperature, since the direction of air flow depends on the season. In winter, when outside temperatures are low, air is sucked in at lower elevated vents and flows out at higher elevated vents; in summer, the pattern reverses. The flow rate is controlled by the temperature gradient between outside air and air in the bedrock fracture system, and reaches up to 1 m³/s. ²²²Rn concentrations are strongly dependent on the air-flow rate and are generally highest (up to 50 000 Bq/m³) when the flow rate is low, but they are also related to the rock-atmosphere contact area which depends on ground water level and the extent of ice in subsurface fractures. Stable subsurface air temperatures at or below 0°C indicate the existence of sporadic extra-zonal permafrost mainly in the rock cliff below the mountain plateau. There, the bedrock reaches its highest temperatures in late autumn/early winter which coincides with enhanced deformation of unstable rock sections along the cliff. Climatic warming leads to changes in bedrock ventilation systems, warming ground and thawing permafrost, and thus influences slope stability.

09.3

Fold-controlled sliding revealed from structure and InSAR data at the Dunsjárga rock slope deformation

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To assess the risk of catastrophic failure from unstable rock slopes the volume, shear zone and kinematic behaviour must first be understood. Slow-moving rock slopes often require time consuming and expensive monitoring and research, such as drilling, geophysical campaigns and on-site instruments to be fully understood. However, traditional field mapping of structures and morphological features combined with surface movement data from InSAR, and ground-based sources gives reasonably good understanding of kinematics and the subsurface for classification for risk and hazard assessment. Dunsjárga is an actively deforming rock slope in Northern Norway, with an area of $1.27 \times 10^6 \text{ m}^2$ sliding about 1 cm/year into the fjord below. It poses a threat to nearby villages from displacement wave impact should it catastrophically fail. Field mapping and structural analysis of the site combined with InSAR and dGNSS data has been integrated to develop a geological model of the site. Structural mapping reveals a non- to well-developed foliation in large scale open-folded metagabbro with several mylonitic shear zones observed in the slope. The foliation is folded in a synform in the toe section of the slope. Displacement vectors from dGNSS and InSAR indicate the deformation follows sliding along this synform structure, with vectors dipping into the upper slope, and up and out of the toe section. We propose that as the rockslide progresses downward into the lower limb of the synform the friction acting against sliding will gradually increase, ultimately leading to stabilization of the rock mass rather than catastrophic failure. To test this hypothesis, finite element analysis will be performed to test these loading conditions. The results of this study will aid the national authorities in revisiting the hazard analysis and add to knowledge of how surface mapping methods of unstable rock slopes can provide understanding of kinematic behaviour.

09.4

Age distribution of rock avalanche deposits in Rogaland, SW Norway

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Systematic mapping based on high resolution (1 m cell size) digital elevation models and aerial photos revealed 24 post glacial rock avalanche deposits in Rogaland province, SW Norway. Such deposits consist of coarse, block-rich material sourced from rock-slope failure scars upslope, and display flow-like morphology that can span entire valley floors. This contrasts with rock-collapse deposits, which build simple cone-shaped aprons and do not show rock-mass flow. Our count is conservative as additional rock avalanches likely detached from steep fjord walls and entered fjords without leaving onshore deposits. Additionally, some deposits might represent deposits of several events whose individual signatures cannot be separated on morphology alone.

In Rogaland, several deposits in the Norwegian landslide database (NVEatlas.no) are classified as “fjellskred”, a term often translated as “rock avalanche” but defined solely by volume ($> 100,000 \text{ m}^3$) rather than the diagnostic morphological criteria. None of these deposits have exhibit landforms indicative of rock-mass flow, and many appear to have volumes well below $100,000 \text{ m}^3$. The misclassified entries largely stem from non-expert judgements registered, for example, in church books. Following this quality check, no historically documented rock slope failure in Rogaland meets the criteria for a true a rock avalanche.

We dated 12 of the 24 newly recognized rock avalanche deposits by measuring the surface exposure age based on terrestrial cosmogenic nuclides concentrations of the upper faces of 3-6 boulders per deposit. Ten of the twelve deposits have internally consistent ages across at least three boulders. One site yielded two distinct age groups, that, after re-evaluation, were split into two superposed deposits: an overlying large rock collapse resting atop an older rock avalanche deposit. A second site forms a natural dam that impounds a lake. Although present drainage leaves the dam at three locations, abandoned downstream channels record significant past drainage changes. We infer that shifting drainage pathways and associated deformation of the dam likely produced highly variable boulder exposure histories, explaining the inconsistent ages.

The distribution of exposure ages span much of the ice-free conditions in the post-LGM period, with five ages younger than 5 kyr, 3 dated to the Holocene Thermal Optimum (HTO, $\sim 8.5\text{-}5\text{kyr}$), and four ages falling between deglaciation and the HTO. There is also no evidence of spatial clustering of avalanche deposit ages. This contrasts with the age distribution observed in western Norway, where most postglacial events occurred during the first two thousand years following deglaciation (Hermanns et al. 2017).

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09.5

Glaciotectonic structural inheritance preconditions large active rotational landslides in Denmark

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Recent nationwide morphological mapping using a LiDAR DEM reveals numerous large (up to 0.4 km²; ≈900 m × 500 m) active rotational landslides along the Danish coast (Luetzenburg et al. 2022; Svennevig et al. 2020). Some of these have >60 houses atop. In a low-relief country such as Denmark (maximum elevation 170 m a.s.l.) with surficial deposits predominantly composed of glaciogenic sediments, the presence of landslides of this size and state of activity was surprising to researchers, locals and authorities alike.

Dynamic preconditioning is primarily controlled by coastal erosion, and groundwater fluctuations (Svennevig et al. 2024). Displacement rates reach up to several decimetres or more per year, peaking in wet winters (Jan–Mar) with elevated groundwater. Climate projections indicate that the groundwater table in Denmark may rise by up to ~0.75 m by 2100 under RCP8.5 (Seidenfaden et al. 2022), implying increased activity potential for Danish landslides.

From morphological mapping, borehole interpretations and newly acquired geophysical data (geoelectrical, transient electromagnetic, and seismic), we find that the landslides are statically preconditioned by the Weichselian glaciotectonic architecture. These complexes often comprise inclined thrust sheets of glacial sediments and high-plasticity Paleogene clay. Extensional reactivation of glaciotectonic thrusts as basal rupture surfaces produces orogenic-style collapse of the glaciotectonic complexes. This explains the large size of the landslides in the relatively moderate Danish topography.

This raises several questions: To what degree is the basal surface of rupture constrained by these thrust faults, and what does that mean for the stability of the landslides? How are groundwater fluctuations and landslide activity linked in these very large but relatively low-relief structures? And what does this mean for our understanding of the stability of glaciotectonic complexes just after they formed?

GEUS is mapping and monitoring some of these landslides in a large research project to understand their occurrence, drivers, and outlook in a changing climate. Findings refine hazard assessments for Danish landslides and provide a process-based understanding applicable to formerly glaciated terrains more broadly.

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09.6 (Keynote)

The second highest tsunami ever recorded

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Over the past century, more than two dozen tsunamis with runups greater than 50 m have been reported. Of these, more than half were in the Arctic or subarctic, with eight in Nordic countries and six in Alaska, including the 1958 Lituya Bay megatsunami, which ran up 530 m in elevation. Many of those megatsunamis occurred in deglaciating fjords or valleys, and almost all were triggered by landslides. At 5:26 a.m. local time on 10 August 2025, a large landslide ($>64 \times 10^6 \text{ m}^3$) collapsed about one vertical km onto South Sawyer Glacier and into Tracy Arm, a cruise ship-frequented fjord in southeast Alaska. The landslide triggered a megatsunami, which reached an elevation of 481 m up the opposite fjord wall before propagating out of the fjord into Stephens Passage and Endicott Arm to the south. The tsunami was experienced by multiple ships in the vicinity, but due in part to its early morning timing, luckily no deaths or injuries occurred.

The initial rock wedge failure transitioned into a rock avalanche as it traveled down the slope and produced globally observed long-period seismic waves equivalent in size to those of a M5.4 earthquake. The landslide was also preceded by more than 24 hours of microearthquakes attributed to slip along the failure surface, with increasing rate and amplitude until roughly an hour before failure. Long-period monochromatic global seismic signals persisted for over 36 hours. These signals are consistent with a landslide-induced seiche trapped in the fjord, an interpretation further confirmed by tsunami simulations and satellite observations.

The landslide and resulting hazard cascade was enabled by >6 km of retreat of South Sawyer Glacier since 1948, which we statistically attribute to anthropogenic warming. Most recently, the base of the failed slope was fully exposed between late June and early August 2025 when the glacier retreated ~ 300 m. A large failure of a slope that had not previously been identified as a hazard, and with no precursory slope deformation, in a fjord with extensive recreational activity (e.g., cruise ships and personal pleasure craft) highlights the near-field risk of landslide tsunamis and underscores the importance of enhanced monitoring and continued research using a variety of tools, including seismic, remote sensing, and in situ monitoring.

09.7

Mass movement triggered glacial lake outburst flood hazard: A perspective from Iceland.

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One of the most conspicuous consequences of climate change in Iceland, as in many mountainous areas worldwide, is rapidly retreating outlet glaciers. Proglacial lakes may form in front of these glacier termini, often in glacially overdeepened troughs. Most Icelandic proglacial lakes can be categorized as lowland lakes, carved into both bedrock and sediments. Since the 19th century high stands of the Little Ice Age in Iceland, Icelandic glaciers have probably lost about 16% of their mass. Warm conditions in the 1920s and 1930s drove rapid glacier retreat in Iceland and resulted in the formation of many proglacial lakes. During the last decades or from around 2000, existing proglacial lakes have expanded, some at an exponential rate, and many new ones have formed.

During recent years, high-resolution multibeam and single beam sonar measurements of lake bathymetry have been carried out on several proglacial lakes in Iceland. These studies have provided valuable data on glacier retreat rate and lake development under ongoing climate change, reconstruction of lake volume changes and lake bathymetry.

These glacier fluctuations can and have affected the stability of neighboring mountain slopes, resulting in slope deformation and mass movements, triggered by various paraglacial processes.

In 1967, a rockslide fell onto an outlet glacier and partly into its proglacial lake in the Steinsholtisdalur valley in South Iceland, creating a large glacial lake outburst flood (GLOF). The GLOF left a trail of ice, rock debris and landscape transformation that entirely overprinted the pre-existing proglacial landscape in the valley.

The potential for mass movement triggered GLOFs in other areas where proglacial lakes have formed has increased considerably over the last decades. Many of these areas both attract tourists year-round and have seen recent related infrastructure development in their vicinities. This development raises serious concerns and stresses an urgent need to study and monitor these environmental hazards.

09.8

Shallow landslides in West Greenland - An emerging climate change-related geohazard

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In 2023, three shallow landslides were reported near Sisimiut and Kangerlussuaq, western Greenland, the first documented cases in the region in over a decade. These events followed periods of intensified rainfall, underscoring precipitation as a key trigger. Shallow landslides pose increasing risks to local communities, infrastructure, and tourism, yet remain poorly described in Greenland compared to other Arctic regions. This study investigates their mechanisms, distribution, and climatic drivers to improve understanding of future geohazards.

During field campaigns, the three reported landslides were investigated through geophysics, UAV 3D-modeling, remote sensing, and samples were collected for geotechnical classification and x-ray diffraction. Weather anomalies preceding the events were extracted via Google Earth Engine, while Sentinel-2 imagery supported NDVI-based comparisons of vegetation removal during landslide events.

All three landslides have soil dominated by sand and silt with minor clasts, underlain by a saturated zone that promoted quicksand-like conditions at the slide toes. UAV models estimate slide thicknesses of 4–6 m. Given that the local active layer averages ~1.5 m (Olesen et al. 2003), these depths indicate talik-like unfrozen zones that enhance slope instability. Notably, analysis of older satellite images shows no or very few previous landslides, but from 2019 to 2024 NDVI analysis revealed 700 additional landslides across a 200 km transect from the ice cap to the coast, at elevations from sea level to >800 m. Most slides occur on south-facing slopes and in years of intensified precipitation.

These findings indicate that intensified rainfall and degrading permafrost are driving new slope failures in western Greenland, consistent with patterns observed elsewhere in the Arctic (Patton et al. 2019). Future projections of permafrost degradation (Slater & Lawrence 2013) suggest further acceleration of this process.

Post-failure processes have also generated hazardous conditions at slide toes, creating an additional geohazard in the form of quicksand. Anticipating future slope instability will require integrating permafrost monitoring, precipitation data, and remote sensing into regional hazard assessments.

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09.9

Anthropogenically Triggered Quick-Clay Landslide Disrupting the E6 Highway for 285 Days, Southwestern Sweden, September 2023

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At around 01:40 a.m. on 23 September 2023, a large landslide occurred at the Stenungsund interchange on the European route E6 highway in southwestern Sweden. The event tore apart both the E6 and a municipal road, dammed a small river, and destroyed several commercial buildings. Within the landslide area, nine cars and one bus were trapped while driving, and eleven professional drivers were in their parked trucks. Fortunately, no fatalities occurred – largely due to the timing of the event at night, when traffic and commercial activity were minimal. Nevertheless, the event caused severe economic disruption, blocking the main transport artery between Oslo and continental Europe, highlighting the vulnerability of infrastructure in sensitive clay terrain.

The west coast of Sweden is known for its sensitive clay, deposited in a glaciomarine environment. Following deglaciation and isostatically induced regression, these clays are prone to leaching and, in places, transformation into “quick clay”. Post-glacial transgressions may also introduce organic-rich layers that further increase instability.

This contribution examines the progressive–translational development of the landslide in relation to the geological setting, stratigraphy, recent landscape changes at the site, and witness statements. It emphasizes the key role of recent human activity in triggering the quick-clay failure. The presentation builds on material first discussed at the 36th Nordic Geological Winter Meeting in Gothenburg (2024), when confidentiality was required due to the ongoing investigation. Thus here, insights from the final report of the Swedish Accident Investigation Authority (SHK) are presented.

Results include geodetic analyses of digital elevation models and photographs, stratigraphy from fieldwork, and morphological and kinematical interpretations. The development of the landslide is reconstructed from these results, together with recorded data from the Swedish National Seismic Network, InSAR, the electricity grid, the heating network, and witness statements, which help constrain the timing of events.

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09.10

Applying machine learning to Denmark's Landslide Inventory

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Landslides have been an underestimated geohazard in Denmark, directly impacting infrastructure and settlements (Svennevig et al. 2020). Climate change is expected to accelerate landslide activity in Denmark, yet, relatively few scientific studies exist (Svennevig et al. 2024). The previously published national landslide inventory documents more than 3200 landslides that were manually mapped based on morphological expression in a national 0.4 m LiDAR DEM (Luetzenburg et al. 2022). However, the inventory requires updates and further development to provide a more complete record of landslide occurrences across Denmark. Here we take the next step by applying machine learning to expand, refine, and conduct quality-control on the national inventory. Further efforts focus on developing AI approaches to detect paleo-landslides and assign landslide activity to recent landslides. The expected outcome is a more comprehensive landslide inventory that will enhance understanding of slope instability mechanisms and provide insights into how landslides may evolve under a changing climate, while supporting enhanced geohazard and risk assessments.

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O9.11

Investigating the geologic and hydrogeologic prerequisites for a catastrophic outburst at Tjärnviksdalen, central Sweden

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Tjärnviksdalen in Jämtland county, central Sweden, is a valley filled with thick Quaternary deposits formed during two glaciations and ice-free periods. Eskers, kettle holes, and fine-grained glaciolacustrine sediments act as a natural dam separating Lake Gesunden from the Indalsälven River. For over a century, concerns have been raised that the river could shift course, deviating from its current path to Tjärnviksdalen, with severe consequences for infrastructure, communities, and the environment. This study presents new geological and hydrogeological results and interpretations with the aim of increasing the understanding of the risk for dam failure based on geological reasoning.

Drilling, geophysical surveys, groundwater monitoring, geomorphological mapping, and 3D modelling provided new insight into stratigraphy and hydrogeology. The stratigraphy reflects two glaciations, with glaciofluvial and lacustrine deposits forming a complex sequence. Coarse sediments dominate in the esker core, while silt and fine sand occur locally. These fine-grained layers are erosion-sensitive but limited in extent. In several locations, a till from the last deglaciation divides the sediments, with older deposits beneath, likely from a previous ice-free period. This till layer is interpreted to provide a stabilizing influence.

Hydrogeological data show groundwater gradients from Lake Gesunden to Indalsälven of 2.5–7 ‰, values near or below thresholds for internal erosion. The dominance of coarse glaciofluvial deposits reduces susceptibility, though silt layers and stratigraphic variability may form weak zones. GIS-based modelling identifies steep slopes as potential initiation areas for debris flows and landslides, but no active erosion was observed in the field.

Three breakthrough processes were evaluated: internal erosion, retrogressive slope erosion, and overtopping. The probability of a large-scale breakthrough is low under current conditions, as the valley has remained stable for over 8,000 years despite major geomorphic changes such as ice-lake drainage, relative sea-level fall, and climatic fluctuations. However, climate change may increase hydrological extremes, groundwater pressures, and erosion, particularly where land use modifies drainage or slope stability.

We suggest that Tjärnviksdalen is generally stable, with limited risk of catastrophic breakthrough, but locally vulnerable to erosion and slope processes under extreme weather and land-use change. Long-term monitoring, careful planning, and further modelling are recommended to strengthen hazard preparedness in a changing climate.

09.12

Geological signatures of storm surges along the southern Swedish coast

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Storm surges combine the power of two natural hazards, strong winds and flooding, and can have devastating effects on people, infrastructure, and nature in coastal areas. Ongoing global changes, including rising sea levels and shifting storm patterns, are expected to increase both the frequency and amplitude of such events in the future. There are, however, significant regional variations and some trends are uncertain. To improve our understanding of the factors and processes that control coastal flooding and increase our ability to assess future risks at time scales relevant for coastal management, we require storm surge records that extend back beyond the instrumental era.

In this pilot study we have explored the coastal sedimentary record at several sites along the coast of Halland and Scania in southern Sweden with the aim of identifying past storm surges. Sites with both known storm surge deposits (e.g. from storm Babet in October 2023) and sites expected to contain traces of older events were investigated. A range of sedimentological, geochemical and dating methods have been applied and tested to evaluate what works best for these types of deposits, including X-ray fluorescence (XRF), X-ray computed tomography (CT), carbon/nitrogen (C/N) isotope analysis, luminescence and ²¹⁰Pb dating, and grain-size analysis.

Storm surge deposits at the studied sites include massive sandy beds or laminae that differ in grain size and/or composition from the normal accumulation, heavy-mineral lamination, and massive shell beds. Most geochemical and dating results are still pending, but preliminary data indicate that at least the upper parts of the studied stratigraphies are young (<100 years) as also indicated by the presence of polymer fibres in some of the sediments. Our results so far indicate that beach meadows may be the most promising setting in terms of number of events recorded (possibly up to nine at site Rosendal), while sandy berm beaches may contain traces of fewer events, but with deposits that are thicker and more easily traceable inland and alongshore.

O9.13

Thermal properties of bedrock influence active layer thickness of overlying sediment

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Understanding permafrost conditions is important for human societies for several reasons, e.g.: In areas with sediment cover, engineered structures must be founded in permanently frozen sediment or underlying bedrock. In sediments, freezing also causes heaving that can put pressure on overlying structures. Additionally, the active layer in sediment and crystalline bedrock is vulnerable to landslides and rock slope failures.

In Central West Greenland, permafrost-related phenomena cause problems to (i.a.) settlements, airports, two UNESCO World Heritage Sites, and the country's longest road under construction between Sisimiut and Kangerlussuaq (approximately 130 km in bee-line). The bedrock geology between Sisimiut and Kangerlussuaq is dominated by different gneiss lithologies that were deformed at various stages, the last of which is the Nagssugtoqidian orogen (1850–1720 Ma), supracrustal units, and steep dykes belonging to the Kangâmiut dyke swarm (e.g., Korstgård et al. 2024). These lithologies have contrasting physical properties, suggesting that they might react differently during yearly freeze-thaw cycles. We test this hypothesis numerically using a 2-dimensional finite element model of a real geological structure (dyke crosscutting gneiss) with transient surface temperatures emulating annual temperature variations. To obtain model input, we measured density, thermal conductivity and specific heat capacity on drill core samples of relevant lithologies.

We model two scenarios: (1) exposed bedrock and (2) sediment covers of different thicknesses. For scenario (1), our model suggests that the active layer may be up to 46 cm thicker in gneiss than in dykes. For scenario (2) models, we find that the underlying bedrock lithology influences the active layer thickness even if the sediment layer is 4.6 m thick, although the effect decreases as sediment thickness increases. Interestingly, the active layer is thicker in sediment overlying dykes than in sediment overlying gneiss, i.e., the opposite pattern to scenario (1). This probably reflects the high heat capacity of dense dykes that act as heat sinks for the sediment during spring warming and autumn cooling. Although not part of this study, the density of buried bedrock might be directly mapped by geophysical measurements and incorporated into numerical permafrost models. In our model predictions, the heat-flow around a dipping dyke is deflected relative to vertical but this effect is too small to have real-world implications.

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O9.14

Impact of human activity and extreme weather event at Falun Coppermine and effects in a heavy polluted site: a multiproxy investigation of peat cores

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The main aim and objective of the investigation is to establish how human activity and extreme weather events can be traced, identified and dated in the peat and sediment stratigraphy. Furthermore, the aim is to investigate the implications of such activities and extreme weather events in an area historically affected by intense mining activity and how contaminants, mainly from mining processes, may have been mobilized and dispersed because of land erosion.

The Falun Coppermine has a mining history stretching back almost thousand years and has long been recognized for its major role in Sweden's industrial heritage. The Falun Mine was operational until 1992 and achieved its peak productivity throughout the 17th and 18th centuries, contributing to the regions and Sweden's economic advancement. Hence, the area is rich in documented history, including notable events such as the extreme weather event in 1666 that occurred 27th of July. The precipitation volumes have later roughly been estimated to at least 5 million m³, assuming a quantity of 220 mm of rain for 3 hours over an area of 25 km². The subsequent land surface flooding resulted in the destruction of infrastructure, housing and materials, as well as extensive erosion of land and assumed present contaminants from the mining activity.

The extreme weather event at Falun Coppermine in 1666 had, according to written records, a severe impact on a limited area, which is pointed out in the descriptions. The area was flushed by water and the surface was eroded and dispersed. The central site in the study is a small bog in the area, difficult to reach and therefore protected from disturbance from activities in the surrounding, back in history and until today. According to written records, this bog lies in line with the surface flooding. A cross transect of coring points was performed in the bog, described and sampled, to find remnants from the extreme event and other impact from the mine. A multiproxy strategy is applied for dating, geochemistry, sediment analysis, biological parameters and macroparticles, to understand the effects of extreme events and mining activity in the area. From long-term, to short-term, to extreme-time event impact on environment and spread of macro- to microparticle contaminants.

09.15

Geant4-based simulations for muon imaging of volcanoes

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This study presents a numerical modeling framework for volcanic muography aimed at imaging the internal structures of large-scale volcanoes through simulations of atmospheric muon flux propagation. Muography utilizes the attenuation of high-energy cosmic-ray muons in dense geological media, enabling non-invasive imaging of volcanic conduits and crater regions. The approach is demonstrated on the Iwodake volcano, located on Satsuma-Iojima Island, Japan, which has been the subject of prior muographic surveys (Tanaka et al. 2009).

Simulations were conducted using the Geant4 toolkit (Agostinelli et al. 2003), providing detailed physics models of particle–matter interactions. A three-dimensional digital elevation model of Iwodake was constructed from Shuttle Radar Topography Mission (Farr et al. 2007) data and combined with geological and volcanological data from the literature. The resulting voxel-based model incorporates spatial heterogeneities in density and composition, reflecting contrasts between solid rock, degassed magma, ascending magma, and collapsed material in the crater.

To investigate dynamic volcanic processes, multiple density configurations were considered, representing different stages of magma convection and degassing. Muon propagation was modeled using a modified parameterization of the Gaisser formula for sea-level muon spectra (Guan et al. 2015), with muons generated from a virtual hemisphere surrounding the volcano. Computational efficiency was enhanced through energy thresholds and a backtracing algorithm to focus on trajectories intersecting detector planes. The detection system was represented by virtual observation planes at realistic field locations. This framework allows the generation of synthetic muographic images and provides a basis for evaluating detector placement, exposure times, and the potential of muography to image internal density variations and monitor volcanic activity.

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O9.16

Earthquakes, Glacially Triggered Faults, and the importance of the Single Modern Earthquake Scarp Height/length (SMERSH) ratio in Fennoscandia

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I compare 315 quality-ranked maximum displacement/length ($D_{\max}/L$) ratios of Earthquake Surface Ruptures (ESR) against 720 $D_{\max}/L$ Geological Fault Systems (GFS) observations. High-quality ESR ratios rarely exceed 0.0002 whereas very, very few, and quality-unknown, GFS ratios are less than 0.001. Mathematical exercises suggest the ESR-GFS gap should not exist in nature. Its empirical presence raises four questions: 1) Might extreme scarps of certain gap-filling Post Glacial Faults (PGFs) represent cumulative displacement from multiple ESRs? 2) If so, why only in Fennoscandia? Should we not find more PGFs elsewhere? And ought there not be $D_{\max}/L$ evidence for incipient fault scarps in tectonically active parts of the world? 3) Given the difficulty in establishing evidence for Quaternary offset throughout much of Fennoscandia, can $D_{\max}/L$ be a first-order tool to help assess claims of neotectonic faulting? And 4): How well do we understand fault growth processes anyway? I present empirical evidence for the ESR-GFS gap. I put the gap to work by proposing a Single Modern Earthquake Rupture Scarp Height/length (SMERSH) cutoff of 0.0002 (>95% confidence) with permissible extension to 0.0004 (>99% confidence) under specific circumstances as helpful pointers towards PGF status. From the perspective of SMERSH I examine and reject Norway's controversial Nordmannvikdalen Feature as a single-rupture PGF. I discuss some general problems of fault growth and multiple-rupture PGFs, including Finland's Venejärvie Jauhojärvi PGF complex. Although I cannot answer any of my four questions to satisfaction I conclude SMERSH does provide a useful tool for assessing proposed PGFs. Individual apparent displacements that by themselves fail SMERSH and cannot be linked with neighbouring offsets to form a single coherent, SMERSH-compliant rupture system were most likely not formed by neotectonic ESRs. Many PGFs should be given serious re-assessment – and any investigation of a suspected PGF must adhere to the strictest standards of paleo-seismic inquiry. Because no presenter can hope to talk their way through all of this under the confines of a 15-minute slide show, my presentation will focus on the data which underlie the development of SMERSH itself. For that which is left unsaid, interested parties may consult (Redfield 2025).

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09.17

Reconstructing historical and Holocene seismicity from lacustrine archives in Nordland, Norway

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In Fennoscandia, the majority of paleoseismic data come from the study of features interpreted to have formed during surface ruptures. Excepting the Stuoragurra fault (as well as rare seismites interpreted from enigmatic raised marine deposits), geological evidence for postglacial surface ruptures in Norway is poor to absent. Here, we summarize a proof-of-concept study that uses lacustrine sedimentary archives to constrain Holocene seismicity in the Ranafjord area, currently one of the most seismically active regions in Norway. Indeed, the epicenter of Norway's largest historical earthquake, the magnitude ~6 Lurøy event of 1819, is hypothesized to lie only a few tens of kilometres northwest of Mo i Rana. Our research questions include: i) did the 1819 Lurøy earthquake impact the sedimentary record of nearby lacustrine basins, and ii) do lacustrine sedimentary archives contain evidence for older, postglacial seismicity?

To date, we have surveyed two lacustrine basins. The first, Silavatnet, lies in a narrow valley at ~29 m asl, approximately 25-30 km west of the hypothesized epicentre. The second, Langvatnet, approximately 10-20 km east of the hypothesized epicentre, is a glacier-fed lake situated at ~40 m asl. Following postglacial uplift, both basins were isolated from the sea during the early to mid Holocene and, as such, contain contiguous records of lacustrine sedimentation spanning the last several thousand years. High-resolution bathymetric models were developed for both lakes following extensive multibeam echosounder surveys using a Kongsberg EM2040P, and a Knudsen *Pinger* CHIRP echosounder was used to collect widespread subbottom profiler data. Sediment gravity flows and mass transport deposits were mapped using a GIS. Deposits were sampled using both a Pylonex HTH gravity corer and a Reasoner-type percussion corer. Multiple, recently deposited turbidites from both lakes were identified and analyzed. In both Silavatnet and Langvatnet, the ages of multiple sandy turbidites are constrained by Pb-210 and C-14 dates, placing them at the appropriate chronostratigraphic position to have been triggered by the 1819 Lurøy earthquake. In Langvatnet, turbidites and mass transport deposits occurring at greater depth were sampled in long sediment cores and traced across the basin in subbottom profiler data. Such deposits suggest a period of widespread subaquatic landslides in the mid Holocene that may relate to a currently unidentified earthquake or earthquakes, possibly of similar magnitude to the 1819 Lurøy event.

Ongoing sediment proxy analyses, radiocarbon dating, and analysis of geophysical data will further constrain the exact age and origin of mapped sediment gravity flows and mass transport deposits. When complete, we hypothesize that lacustrine basins, such as those surveyed in this study, may be a new resource for reconstructing postglacial Fennoscandian seismicity.

P9.1

Holocene storminess in Lofoten, NW Norway, reconstructed using aeolian sand influx and X-ray micro-computed tomography

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Ongoing global warming is expected to affect patterns of weather events in Scandinavia, including the intensity and frequency of storms, i.e., *storminess*. Predictions of future storminess are however, uncertain and often conflicting, owing to the complexity of the climate system as well as a lack of sufficient long-term data on past storm variability. As instrumental records of storminess cover at most a few hundred years, proxy-based reconstructions are fundamental to the understanding of past storm variability. In Scandinavia, the quantification of past aeolian sand influx (ASI) to peat bogs is a proxy method often used for reconstructing storminess. The method assumes that sand grains found within ombrotrophic peat must be of aeolian origin, as the bogs are hydrologically separated from their surrounding environment. Thus, past wind climates can be inferred by quantifying the variability in sand content with depth/age in ombrotrophic peat.

In this project, we apply for the first time an X-ray micro-computed tomography (μ CT) based method for quantifying ASI to a Holocene-age peat sequence from Gimsøya in Lofoten, NW Norway. μ CT is a non-destructive imaging technique that allows for μ m-scale cross-sectional visualization and quantitative analysis of the internal structures of objects based on density. By employing the μ CT based method, we aim to produce a continuous ASI record with high temporal resolution, potentially resolving sub-decadal storm variability in a multi-millennial peat sequence. Additionally, we aim to remove potential noise introduced in the high-temperature dry ashing phase of conventional ASI analysis, while also vastly reducing the time and labour costs of analysis.

The Gimsøya peat core was μ CT scanned with a voxel resolution of 30.05 μ m, which enabled quantification of ASI and grain size distribution for sand grains $\geq 125 \mu$ m with data binned into 1 cm depth intervals. Preliminary results show sand content varying between 0–31 grains cm^{-3} throughout the sequence, with a median of 2.4 grains cm^{-3} . This is similar to the sand content recorded in peat sequences from previous ASI studies based on established analysis methods (cf. Björck & Clemmensen 2004; Vaasma et al. 2025), which affirms the robustness of the μ CT method. These results further confirm the potential of the μ CT-based ASI method to fill existing knowledge gaps in past storm variability.

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P9.2

Inventory, morphometric analysis and modelling of debris flows in central Sweden

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Debris flows are geologic features that form by saturated material that flows down gradient. As they make their way down gradient they can incorporate more materials, including boulders, logs or tree stumps; making them a serious threat to infrastructure and human life. Debris flows are often triggered by heavy rainfall or snow-melt, and the land use within the upstream watershed is an important factor in mitigating the risk of severe consequences.

Debris flow geohazard maps are important for policy makers, landowners, and the general public to make informed decisions. As a part of an overarching European Union Interreg project, led by the Swedish Forestry Agency, we have produced an inventory of landslides and debris flows in the counties of Västernorrland and Jämtland, central Sweden. The landforms are mapped with a focus to retrieve morphometrical information as well as a classification of debris flow and land slide types. Västernorrland and Jämtland are high-relief areas and therefore highly susceptible to debris flows. Forestry is a dominant land use in the region and has a major impact on slope stability and hydrology. Sustainable forest management in these landscapes requires high-quality geographic information, including geological maps and susceptibility assessments.

We use the new inventory of initiation points and depositional areas to calibrate the Gravitational Process Path model (Wichmann 2017). The model simulates process paths and run-out areas of debris flows from terrain, sediment, and bedrock data, providing maps of areas with elevated susceptibility. These maps highlight where forestry planning and infrastructure development must account for debris flow hazards.

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P9.3

A new national inventory of past rock avalanches in Norway

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Over a thousand large unstable rock slopes have been identified in Norway, some of which pose a major threat to society through their potential to fail as rock avalanches – extremely rapid (granular) flows of fragmented rock. Given the scarcity of historical examples on which to build robust predictions, the geological record is essential to better constraining the likely spatial distribution, controls, and runout of rock avalanches in Norway. We present results from national-scale systematic mapping to identify and classify rock avalanche deposits and their associated former source areas. Deposits were mapped where they display diagnostic flow-type morphologies, including blocky carapaces, transverse pressure ridges, longitudinal furrows, run-up/overspills, and valley-spanning (often lobate) tongues.

Our inventory includes ~300 onshore rock avalanche deposits, which are broadly distributed over the entire country, but are found in higher density in over-steepened fjord and inland valley systems in the southwest (Møre og Romsdal, Vestland) and north (Nordland, Troms) of Norway. Many additional rock avalanches terminate partly or entirely in fjords, and are reserved for future work coupling onshore mapping with marine bathymetric and/or seismic data. The onshore deposits are classified according to morphology of the runout path (open-slope/unobstructed, channelized, valley-spanning), mobility (H/L, reach angle), lithology of the source, and substrate along the runout path.

Given the first-order role of volume in runout, we reconstructed volumes for ~200 deposits using DEM-based approaches (e.g. Sloping Local Base Level, polynomial curve fitting, reconstruction of pre-event contours) that were tailored to runout path type. Where detailed reconstructions were not feasible, we assigned a magnitude class using simple empirical estimates. The deposit volumes span a magnitude range of $\sim 10^5$ – 10^8 m³, with a median deposit volume $\sim 10^6$ m³. ~45–55 % of deposits have volumes under $\sim 10^6$ m³, which is traditionally considered typical for rock avalanches, highlighting that confinement, substrate, and other factors – not just volume – contribute to mobility. Finally, we assess runout-length variability across path morphologies and compare volume–mobility relations (H/L) against cases worldwide.

P9.4

Permafrost landscapes in a changing climate – Effects of thermal erosion on slope stability on the coast of Forkastningsfjellet, Svalbard.

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Accelerated climate warming within Arctic latitudes promotes permafrost degradation, fundamentally reshaping landscape organization. Thawing permafrost and thus related associated thermokarst processes impact entire ecosystems, infrastructure, and economic development, thereby increasingly threatening Arctic communities. Permafrost thaw also enhances slope instability, which in turn may cause landslides capable of generating displacement waves. Despite urgent need to monitor, quantify and finally predict these processes (and chains thereof), scarce observational data limits our current understanding.

Forkastningsfjellet, situated along the eastern margin of Isfjorden, Svalbard, exemplifies such rapidly changing coastal mountain environments which might serve as a model for the future scenarios of polar coastal landscapes. Here, we merge integrated, cross-platform datasets – drone imagery, satellite data, in-situ surface temperature measurements, bathymetry and dGPS – to quantify key processes and landscape dynamics including erosive sediment transport.

Over the last 8 years, we have documented accelerating surface deformation and thermo-erosive activity, which has led to subsurface drainage, sinkhole and tunnel formation along pre-existing fracture zones. The reorganization of the drainage pathways and resulted increase of hydrological connectivity facilitated deep percolation of relatively warm surface waters, thereby reducing the stability of the permafrost bedrock within the cliff. As a result, the most recent rockslide (November 2022) was promoted by thawing of formerly ice-bonded cracks and increasing pore water pressure. Due to ongoing head scarp retrogression, active gully formation and the emergence of new sinkholes at structural weaknesses, cliff collapse and surface mass transfer will most likely propagate southward.

Our results provide fundamental insights into future engineering-geological hazard scenarios in Arctic coastal regions. In light of predicted intensified Arctic warming, the potential reactivation of large, yet currently dormant post-glacial rockslide complexes must be carefully considered in future planning and development activities along Arctic coasts.

P9.5

The enigmatic mass movement inventory of Langvatnet, Nordland, Norway – a slideshow

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Gravitational mass movement processes are widespread in Norway. On land they can be detected on high resolution topographic data and/or aerial photos. Subaquatic mass movements are hidden under the water surface, occur in most cases silently but can, depending on size, be widespread and devastating on underwater or near-shore-infrastructure. Subaquatic mass movement processes in lakes have often less impact. However, their magnitude, frequency, age, and high preservation potential make them a valuable archive for past and present environmental and climatic changes and extreme events, such as earthquakes.

Langvatnet is located a few kilometers north of Mo i Rana, Norway. The 24 km² L-shaped lake is located at 40 m asl. The lake is glacier-fed through the main inlet in the west and an intermittent inlet in the east. An extensive multibeam echosounder survey using a Kongsberg EM2040P revealed a simple E-W elongated basin shape with a maximum water depth of 80 m and deltas in front of the inlets. Along the northern shore, as well as sections of the southern shore, the steep slopes of the surrounding terrain descend into the lake. Using a Knudsen *Pinger* CHIRP echosounder, ca. 150 km of subbottom data reveals a sequence of stratified postglacial sediment across the basin, which is punctuated by various sediment gravity flows and mass transport deposits. In total 27 sediment cores were collected using a Pylonex HTH gravity corer and a Reasoner-type percussion corer. Of these, a selection was split and investigated using GEOTEK and ITRAX multi-sensor core loggers.

The results show rhythmically-laminated, silt-clay couplets from the lake floor to depths of 5-6 m. It is hypothesized that intervals of this sedimentary sequence include periods with seasonal to annual resolution. Occasional turbidites contrast with the rhythmites, illustrating that quiescent sedimentation from suspension was intermittently disrupted by episodic slope processes. Sediment cores have been investigated using X-ray imaging, XRF scanning, and magnetic susceptibility. Ongoing C¹⁴ AMS and Pb²¹⁰ dating is being used to establish an age model. Additionally, grain size analyses, thin-sections, CT scans, and a detailed analysis of XRF results are enabling the development of a robust model of the dominant sedimentary processes operating in the lake and will constrain the precise age and origin of turbidites and mass transport deposits. We hypothesize that a recent turbidite in the sediment cores may be linked to the 1819 Lurøy earthquake, with a presumed epicenter only tens of kilometers away. Basin-wide correlations of older turbidites and mass transport deposits using sedimentology, geochronology, and subbottom profiler data may help identify earlier palaeoseismic activity in the region. We propose that reconstructions of lacustrine sedimentary archives and understanding pre- and post-seismic sedimentary processes, have the potential to constrain postglacial paleoseismicity in Norway.

P9.6

A National Effort to Catalogue Historic Debris Flow Hazards and Associated precipitation thresholds in Sweden

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Debris flows are fast and unpredictable natural hazards that have paralyzed communities in several locations worldwide. The risk of debris flows occurring in Sweden is increasing due to urban exploitation and climate change. The effects of climate change are expected to be most severe in the Swedish mountain region, with steep mountain slopes being particularly sensitive. This is due to a projected future increase in precipitation, including extreme events, which may lead to changes in stream flows, surface runoff, and soil saturation. We are therefore launching the—*Temporal and AReal dynamics of Debris flows and their Impact on Swedish society (TARDIS) and infrastructure in a changing climate*—project to advance knowledge on debris flows in a Swedish context. TARDIS aims to reduce society's vulnerability to debris flows by analyzing the spatial and temporal distribution of debris flows and extreme rainfall, and develop a regional risk assessment, with a focus on municipalities and infrastructure within the Swedish mountain region.

As a first step to develop an analytical framework for assessing debris flow risk, we present a compilation and evaluation of historic debris flow events in Sweden. A systematic inventory is conducted by combining structured screening of Swedish news media, rescue service incident reports from public agencies, existing hazard databases, and scientific literature. These sources form the basis for a coherent database of historic debris flow events, including georeferenced locations, timing of events, and associated uncertainties. We also present a first order assessment of associated rainfall triggers, by coupling recorded debris flow events to relevant available precipitation data from analogue and automated weather stations and gridded reanalysis data (1961-2021) with 4x4 km spatial resolution and daily temporal resolution. We subsequently assess to what degree the observational and gridded products for Sweden can be used to couple benchmarked debris flow events, to draw lower-bound lines of rainfall estimates (precipitation thresholds). As part of TARDIS' long-term goal, our database effort lays the groundwork for subsequent modeling of historic and future debris flow susceptibility and climate conditions which will inform participatory workshops with local stakeholders to co-develop monitoring strategies and enhance regional preparedness.

P9.7

EPOS-NG: The Norwegian Infrastructure for Multidisciplinary Geohazards Research

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The EPOS-Norway—Research Infrastructure for Geohazards (EPOS-NG) is a transformative five-year initiative (launched March 2025) funded by the Research Council of Norway. As the successor to EPOS-Norway Phase 1, EPOS-NG establishes the premier national infrastructure for geohazards research, focusing on landslides, tsunamis, earthquakes, and cryospheric hazards.

The project will deploy new, national pools of cutting-edge instrumentation, including rapid-deployable seismometers, ocean bottom seismographs, Distributed Acoustic Sensing (DAS) and Distributed Temperature and Strain Sensing (DTSS) systems, Transient Electromagnetic equipment, piezometers, self-potential sensors and ground-based interferometric radar systems. This enhanced observational capacity will catalyze research into critical processes such as slope stability, landslide dynamics, and cryosphere changes.

A central pillar of EPOS-NG is the development of a state-of-the-art data portal, building upon the existing EPOS-N platform. This portal will provide integrated access to diverse geoscience data, computational tools, and visualization services, strictly adhering to FAIR (Findable, Accessible, Interoperable, and Reusable) principles. By integrating new instrumental data with novel services for tsunami hazard assessment and innovative datasets—such as InSAR displacement trends and paleoseismological records—EPOS-NG will enable groundbreaking, multidisciplinary studies.

Uniting key institutions across Norway, EPOS-NG represents a unifying national infrastructure that integrates physical assets and data services to address urgent geohazard challenges in a changing climate. To ensure broad relevance, user panels representing research, education, industry, and risk management will provide feedback throughout the project. The ultimate aim is to foster innovation through improved data interoperability and user-friendly services, ensuring broad accessibility for both academic and practical applications.

P9.8

A new national seismic hazard assessment for continental Norway and the Svalbard archipelago

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A new probabilistic seismic hazard model for Norway and the Svalbard archipelago has now been published. The study follows recent advancements in earthquake hazard estimation and is driven by new methods, tools, and complex processing routines and calculations. Norway, located on the western edge of the stable Fennoscandian shield, experiences low to moderate seismicity, with events rarely exceeding magnitude 5.5. In contrast, Svalbard has seen moderately sized events close to population centers in recent years. The study area encompasses continental Norway and the Svalbard archipelago, including a 300 km perimeter. Hazard estimates are calculated using the OpenQuake Engine, with input data sourced from the Norwegian National Seismic Network and supplemented by other national and international catalogs. The catalogue represents a significant improvement, with the addition of five years of earthquake data, a lower minimum magnitude, automated quality assurance, and data harmonization with neighboring regions. The study is supplemented by a smoothed seismicity model, in addition to traditional area zonation, and the applied ground motion models are validated against local data records. The analysis has resulted in an up-to-date and improved open-access evaluation of seismic hazard in Norway. This new hazard model supports better preparedness and enhances understanding of the economic and societal risks posed by earthquakes. The methods and input data used for the analysis will be presented, along with results, and discussed in the context of ESHM20 and other regional hazard assessments.

O10.1 (Keynote)

4D Kinematic Geomodelling with GemPy

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Understanding subsurface structure is critical for underground construction, mineral exploration, and nuclear waste disposal. Conventional models are largely static, despite the Earth's inherently dynamic nature. Tectonic processes generate evolving geometries that are difficult to represent in three dimensions alone. Existing approaches to 4D geomodelling include PDE-based formulations (Bangerth et al. 2024), kinematic reconstructions (Dahlstrom 1969) or geostatistical methods (Mallet 2004) to address this problem.

Commercial 3D kinematic modelling tools, such as MOVE and Kine3D, implement similar assumptions, including rigid block rotation, constant bedding length during unfolding and imposing a single shear direction (Moretti 2008). However, they depend on explicit surface or volume meshes, making results sensitive to mesh quality and pinning definitions (Wellmann & Caumon 2018).

We introduce a four-dimensional space–time interpolation framework that combines implicit geometry representations with universal cokriging via the potential-field method (Lajaunie et al. 1997). By treating time as a fourth dimension, Earth's structure is conceptualized as a hypersurface, observed through three-dimensional spatial projections. Temporal interpolation is anchored at intervals of steady-state deformation, while spatial anisotropy extends applicability to non-cylindrical and non-planar fault geometries.

The method is implemented in the open-source Python package gempy (Varga et al. 2019), ensuring reproducibility and accessibility. Application to the Gullfaks Domino System demonstrate the restoration of non-rigid fault blocks and complex fault geometries.

This 4D implicit interpolation framework provides a dynamic, flexible, and reproducible approach to subsurface modelling, that can inform the time-evolution of 3D geological objects and mineral systems.

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O10.2

Hydromechanical modelling of poro-(visco-)elasto-plastic deformation and multiphase flow in magmatic and siliciclastic reservoirs

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Our main focus is on examining how brittle deformation and the resulting dynamic evolution of permeability influence pathways of localized fluid migration. These processes are well documented in both sedimentary reservoirs and magmatic systems. Key applications include induced seismicity, fault reactivation and cap-rock integrity in siliciclastic reservoirs, as well as dike and sill emplacement with associated seismicity in magmatic environments.

In our models, we consider fluid flow within a deformable porous medium. The governing equations are derived from conservation of mass and momentum for two phases. The first phase represents the solid skeleton, which deforms in a poro-(visco-)elasto-plastic fashion. The second phase describes one or more low-viscosity fluids (water, CO₂, melt) percolating through the solid skeleton according to Darcy's law. A key process of interest is brittle failure of the solid matrix triggered by elevated fluid pressures (hydrofracturing, fault reactivation, diking). The coupled system of equations is solved numerically using the pseudo-transient method, which is well suited to highly nonlinear problems, as it enables solving global equations while simultaneously handling nonlinearities. Additionally, the method involves many inexpensive local operations, making it well adapted for GPU implementation.

We show that our newly developed numerical codes can capture critical end-member cases of fluid-induced fracturing (mode-I and mode-II). Beyond this, we extract components of seismic moment tensors from poro-elasto-plastic geomechanical simulations. This integrated approach links geomechanical parameters with seismological observations, offering a promising pathway toward a deeper understanding of progressive deformation processes driven by fluid migration.

O10.3

3D geological maps to support urban underground planning

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Information about soil layers and bedrock composition and structure is crucial both in the planning and implementation of major infrastructure projects. However, valuable geological data from completed infrastructure projects are not always consistently preserved. The Geological Survey of Sweden (SGU) strives to collect, store, and provide geological information from external stakeholders to improve this situation. This 'recycling' of externally sourced information, when processed and integrated with SGU's own data, enhances the geological input to the planning of future construction and infrastructure initiatives.

SGU has previously developed a regional 3D bedrock map of Gothenburg municipality and a report detailing the area's bedrock, soil types, and geological development. Recently, SGU has significantly updated the interpretation of soil layers, integrating borehole data from external consultants' boreholes and modelling fracture zones in the bedrock, based on extensive public and confidential infrastructure tunnel projects. A further update of the Stockholm urban area is currently underway.

The 3D maps are intended to enhance early-stage project planning and although only models, it is hoped to help reduce risks and improve economic planning in early project phases.

The resulting models, reports and underlying data are all presented and made available on the web with the cooperation of the Polish Geological Institute (PGI) and their Geo3D visualization system.

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O10.4

The crustal scale structural architecture of the Peräpohja belt revealed by integration of seismic, gravity and geological data

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The Paleoproterozoic Peräpohja belt in northwestern Finland hosts several gold- and base metal occurrences and is considered highly prospective for new discoveries. Some of the recognized key components of mineral systems in Peräpohja belt include crustal-scale faults which are inferred to be linked to the rifting of the Archean basement, and the evaporitic Petäjäskoski formation, whose importance as a ligand source is being increasingly recognized.

The aim of this study is to create a crustal scale 2D/3D model of the Peräpohja belt by integrating newly acquired reflection seismic, ground gravity and airborne geophysical data (magnetics, EM) with outcrop observations. Special focus in the model is given on the key mineral system components, the fault architecture, the Archean basement, and the Petäjäskoski formation.

3D reflector orientation analysis (Calvert 2017) performed for the 70-km long reflection seismic profile acquired across the Peräpohja belt, provided accurate location and orientation (dip and strike) of individual reflectors along and near to the seismic line. The data was used to construct the 3D models of the fault architecture and stratigraphic contacts. In gravity data, the Petäjäskoski formation is clearly distinguishable from the overlying Jouttiaapa formation due to its lower density, enabling effective 3D gravity modelling.

The resulting 3D model provides a representation of the structural architecture of the Peräpohja belt, including the geometry of the Petäjäskoski formation, the depth of the belt, the topography of the Archean basement, and the character of the Peräpohja thrust fault system. The results support the hypothesis that Archean basement structures influence fold-thrust systematics of the Peräpohja belt (Piippo et al. 2019).

This study provides important interpretations on the structural and stratigraphic framework of the Peräpohja belt that could have implications in constraining criteria related to ore formation.

This study was carried out as part of the REPower-CEST “Clean Energy System Transition” project, which received funding by the European Union (number 151, P5C1I2, NextGenerationEU).

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O10.5

Atlas of geological 3D models of mineral deposits in Sweden

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The Geological Survey of Sweden (SGU) integrates 3D geological modelling within its geological mapping program and directive for UNFC-classification of mineral deposits (see also Critical Raw Materials Act 2024 and United Nations 2019).

At the department of mineral resources, geologists, geophysicists and geochemists model together by using advanced and interlinked software packages, such as Leapfrog Geo, SKUA-GOCAD, Geosoft and ioGAS. The resulting geomodels provide 3D information and interpretations of the subsurface ranging from 10 m to 10 km depth, which is useful for decision making in exploration and extraction of primary and secondary natural resources, and to enhance geological understanding in general.

Examples of 3D models will be presented for the Riddarhyttan ore field (Fe-Cu-Co-REE), the Enåsen epithermal Au-Cu-Te deposit and Los-syncline (Fe-Cu-Co-Ni) in central Sweden. Interesting results derived from crustal-scale models, experimental sand-box models and drill core models are also included.

All these models, and many more models to come, will be compiled into the “Atlas of geological 3D models of mineral deposits in Sweden”, providing standardized geological frameworks and valuable insights for future underground exploration and research worldwide.

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P10.1

The sinkhole conundrum of the Chicxulub impact crater, Yucatán Peninsula, Mexico: Insights from scaled physical experiments

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Karst-induced sinkholes in Pliocene strata, the youngest sequence of Tertiary sedimentary rocks covering the 66 Ma Chicxulub meteorite impact crater, form a semicircle that is congruent with the underlying crater margin as imaged by gravity anomalies. The causal relationship between the crater margin and the formation of the sinkholes has remained elusive since the discovery of the Chicxulub crater more than 30 years ago. Ground water flow of the northwestern Yucatán aquifer calls for the presence of prominent structural discontinuities in Tertiary strata above the buried crater margin, which likely control sinkhole formation. Based on the analysis of high-resolution satellite scenes, we mapped the ellipticity and respective long axes of some 6500 sinkholes. Assuming that the sink hole long axes represent traces of subsurface dilation fractures and, thus, orientations of maximum principal stresses, the angular departures of these stresses from the uniform regional trend point to local stress perturbations above the crater margin. The patterns of these perturbations agree with experimentally produced ones observed in scaled numerical and physical models, in which model craters are embedded in elastic materials and subjected to uniaxial compression. Moreover, concentric fractures preferentially form at model crater margins in physical experiments simulating cratering-induced crustal relaxation on the order of hundreds of thousands of years. We conclude that the localization of sinkholes in Pliocene strata above the Chicxulub crater rim is the combined result of the concentration of ambient stresses at the crater rim and the consequent reactivation of concentric fractures and their propagation into the overlying Tertiary strata.

P10.2

Kinematic analysis of brittle shear faults generated by the Chicxulub meteorite impact, Mexico, and comparison to numerical modelling

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Kinematic analysis based on the inversion of brittle shear faults is novel in studies of impact cratering. IODP-ICDP Expedition 364 drill core from the Chicxulub impact crater is pervasively affected by decimeter-scale brittle shear faults. Measurements of the orientations and slip senses of 602 shear faults in shocked granitoid target rocks resulted in a unique fault-slip data set of unprecedented detail. The shear faults most likely represent a late stage of cratering, during which the peak-ring formed and the crater grew horizontally. Based on numerical models, deformation during this stage is characterized by concentric and vertical extension and uniform radial shortening. Extracting principal strain axis directions from the inversion of brittle shear faults allowed us to test to what extent the observed brittle deformation corresponds to the deformation regime predicted by numerical models. Moreover, our work explores to what extent fault-slip inversions of impact-induced brittle faults can contribute to the general understanding of crater formation. As the fault-slip data were measured on drill core segments in horizontal position, the data had to be rotated back with regard to the in-situ positions of the segments prior to inversion. Results of the inversion show that the principal directions of observed brittle strain contain the numerically predicted directions for parts of the drill core. Yet, with drill core depth, different deformation regimes alternate, some of which are not evident in the numerical model. Thus, the orientations of the principal strains based on ground truth are more variable than proposed for the apparently simple strain regime during late-stage crater growth predicted by numerical models. Similar to non-impact tectonic settings, we conclude that the variation in principal strain directions inferred from fault-slip analysis portrays kinematic complexities arising from structural discontinuities.

P10.3

Exploring Paleoproterozoic tectonics and its implications for orogenic gold formation using geodynamic models

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Secular cooling of the mantle is generally accepted as the driver for Earth's tectonic evolution, but when and how transitions between regimes occurred, and how different they were compared to modern plate tectonics remains a debate. The Paleoproterozoic Era (2.5–1.6 Ga) comprises one of these transitional periods (e.g., Fischer & Gerya 2016), characterized by a hotter thermal regime than modern Earth. These conditions likely affected the tectonic style, lithosphere rheology, and more localized processes, such as orogenic gold formation. However, the limited Precambrian geological record hinders our understanding of these possible tectonic differences and how they affected the development of mineral systems during that time. Through geodynamic modeling, these past scenarios can be reconstructed in a simplified manner over a wide range of spatial and temporal scales. This study uses 3D thermo-mechanical geodynamic models to explore how thermal conditions during the Paleoproterozoic may have influenced crustal-scale tectonic processes involved in the formation and preservation of orogenic gold deposits compared to younger mineral systems based on modern-day plate tectonics.

The 3D geodynamic modeling code DOUAR (Braun et al. 2008) was used to model the transition from oceanic subduction to continental collision under varying thermal regimes, allowing the simulation of Phanerozoic- and Paleoproterozoic-like scenarios. The models showed that elevated crustal radiogenic heat production in the Paleoproterozoic scenarios was the main factor controlling upper crustal temperatures and deformation, promoting wider and deeper zones favorable for orogenic gold formation. The models also suggest that oblique plate convergence may play a significant role in the formation of hypozonal deposits and overall preservation potential. Despite the simplicity of the model design, some of the features produced by the geodynamic models have been observed in natural mineral systems, such as first-order structures and their association with favorable zones for orogenic gold deposition. This study shows the potential of geodynamic modeling to investigate ancient ore forming processes, which can aid in exploration targeting. However, additional constraints are needed to improve prediction accuracy, including lithological associations with fluid and metal sources, higher resolution imaging of lower-order structures that host most deposits, and clarification of the physical mechanisms that could allow fluid and metal migration from source to final depositional sites.

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P10.4

Development of hydrostratigraphical grid models for the assessment of subglacial erosion in the Northwest German Basin during past and future glaciations

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During the Middle and Late Pleistocene, the Fennoscandian ice sheets repeatedly advanced into northern Germany. Subglacial meltwater erosion led to the formation of tunnel valleys, which are commonly 200 to 300 m deep. Maximum depths of tunnel valleys are up to 600 m. Consequently, the potential formation of tunnel valleys in the future is of critical importance when assessing the long-term safety of potential high-level radioactive waste repositories. The project “Dynamical modelling of subglacial meltwater erosion” aims to quantify the erosive potential driven by meltwater during anticipated future glaciations in northern Germany.

To assess this potential, we have developed an advanced model for subglacial erosion on soft beds, which requires accurate subsurface data. In a first step, we created subsurface grid models for Lower Saxony, which extend to depths of up to -2000 m a.s.l. These models capture groundwater flow around salt structures within deep secondary rim synclines. By using a layered structural model, voxel grid approach, we developed grid models of varying sizes that represent the hydrogeological properties of the stratigraphical units.

The models consist of a structural framework model for the Neogene to Permian depositional units and for the Quaternary depositional units. To simplify the complex depositional subsurface architecture, we used existing hydrostratigraphical classifications for the model region based on Reutter (2011) and defined simplified model units based on these. Lithostratigraphical data from boreholes, cross-sections, and literature enabled us to populate the reservoir grid models with simplified hydrogeological properties. Our grid models integrate constant permeability values that reflect the hydrogeological properties of the stratigraphical units, allowing rapid grid construction even with a highly heterogeneous data set.

These new three-dimensional grid models represent the first comprehensive hydrostratigraphical grid models for Lower Saxony, incorporating deep borehole data. Numerical modelling of meltwater erosion and groundwater flow under the ice sheet that utilises the hydrostratigraphical grid models suggests a high potential of deep erosion in subglacial meltwater channels and forced groundwater flows modulated by the thickness of the overlying ice. Additional insights into soft-sediment deformation and erosion are derived from analogue experiments employing a ring-shear apparatus in Aarhus University's laboratory. The numerical erosion modelling results from models with varying resolution will be compared to examine the effects of lithological resolution and hydrological variations. This research will assist in evaluating the long-term safety of potential high-level radioactive waste repository sites in northern Germany by estimating maximum subglacial erosion depths during future glaciations.

Reference: Reutter, E., 2011. Hydrostratigrafische Gliederung Niedersachsens. Geofakten 21, 11 pp.

P10.5

3D reflector orientation analysis to support geological modelling: case study from the Peräpohja belt, Finland

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Reflection seismics is indispensable for understanding the structural framework of the crust and providing important constraints for 3D geological modelling. 3D reflector orientation analysis can reduce the non-uniqueness inherent in interpreting data from 2D crooked seismic profiles acquired over complex geological structures. This method was recently tested along a new 70-km long reflection seismic profile acquired across the Palaeoproterozoic Peräpohja belt (PB) in northern Finland.

PB consists of a supracrustal sequence deposited between 2.44 - 1.92 Ga during multiple rifting and extensional stages of the Archean basement. The supracrustal sequence of the PB was multiply deformed during the Svecofennian orogeny between 1.92 - 1.77 Ga. Complex deformation resulted in formation of complex fold interference pattern and intrinsic network of thrust and shear zones. Thanks to its mineral systems and potential, the PB was chosen as a test site for the national exploration concept with the collection of new seismic and gravity data.

3D reflector orientation analysis estimates the dip and azimuth of the strike direction of reflections (hereinafter referred as reflection orientation attributes, ROAs) using pre-stack seismic data. ROAs can be recovered only when sufficient azimuthal coverage is present. In case of the new profile, the range of available azimuths was increased by the deployment of additional receivers in form of cross-spreads. The analysis results in an optimally stacked section (with an increased coherency as compared to normal stack) together with the dip and strike attributes. They can be displayed using traditional “static” seismic section plots, but the ROAs form a 3D point cloud around the seismic profile, which can be imported to a geological modelling software and visualized in 3D, e.g. as discs with dip and dip direction of the reflector.

In case of the multiply deformed PB, the reflective lithological contacts show complex orientations. ROAs allowed detailed 3D modelling of folded strata in areas where the stacked section shows merely a blurred cluster of reflectors. 3D point cloud of ROAs combined with surface observations (both geology and geophysics) gives 3D depth constraints on individual geological features. Breaks in ROAs point cloud data form distinct lineaments, which can represent younger faults crosscutting the stratigraphy, and which are important for the metallogeny of the PB. On a larger scale, the new seismic data portrays the thrust-and-fold belt nature of the PB, indicating also the role of the Archean basement topography in the development of the belt.

Acknowledgments

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P10.6

From outcrop to seismic: simulating seismic signatures of complex and small-scale geological features in a flexible and robust manner

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Seismic reflection provides useful images of subsurface geology. Although seismic imaging is a well-established tool in the hydrocarbon industry, its high cost and limitations in resolution and detectability can restrict its broader applicability to other sectors. The interpretation of large-scale features is common practice, but features below a certain threshold, commonly referred to as sub-seismic, may be overlooked. Thin and steep features such as faults, fractures, karsts, intrusions, etc, may be especially misinterpreted or ignored. Understanding how geological features impact seismic images is however essential for effective seismic interpretation in all applications. We use here the case of sand intrusions to illustrate our modelling workflow.

Detailed outcrop models can be used as input to Point-Spread Function convolution modelling, generating seismic models comparable to pre-stack depth-migrated images and that also capture diffraction effects. The geological outcrops used here as example exhibit a wide range of geometrical variations, with intrusion thicknesses extending from metre- to decametre-scale and dips from horizontal to vertical. Pending that the generated geomodels retain a high level of details, this modelling approach generates realistic seismic models directly comparable to the input geology; This, in turn, enables a deeper understanding of the seismic response of specific geological features, constraining limitations in illumination, detectability and resolution.

Comparing input geology and modelled seismic reveals that geological features may be misrepresented in seismic images. In our case, several sandstone intrusions considered seismically resolvable interact with the host rock resulting in disturbed reflectors. Thin intrusions that may otherwise be ignored create unique seismic responses that give indications of their presence, while steeply dipping features induce variations in amplitudes even if not illuminated. The combination of multiple geological features in close proximity results in specific seismic signatures which can be analysed to derive specific interpretation workflows according to the geology of interest.

The capacity to link outcrop models with their modelled seismic response creates an opportunity to unravel how these features manifest in actual seismic data providing improvements to seismic interpretation, especially by developing specific analysis tools (attributes, AI approaches, etc). The seismic modelling workflow from outcrop model can be applied to any complex geological features and provides a de-risking tool for seismic imaging

P10.7

Overcoming Challenges Specific to Modelling Multiphase Fluid Flow in Basalt Reservoirs

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Carbon capture and storage (CCS) is an essential strategy to mitigate the climate altering effects of CO₂ emissions from hard to abate sectors. A potentially impactful CCS strategy is targeting mafic and ultramafic reservoirs for CO₂ injection, where carbonation reaction can take place, locking the CO₂ on geological time scales. Basalt reservoirs are a type of mafic reservoirs which are common and accessible at several locations in Northern Europe and around the globe.

Modelling porous fluid flow in basalt reservoirs is challenging compared to siliciclastic reservoirs for two main reasons. One of these challenges is while siliciclastic reservoirs are relatively homogenous when the flow properties are compared on different length scales (from cm to km), basalt reservoirs are often extremely heterogenous. In basalts flow properties are often dominated by networks of fractures and vesicles, the rock matrix itself is often nearly impermeable. The other challenge is related to reactive flow and how dissolution, precipitation and chemical alteration of the host rock influence fluid properties.

We will discuss potential solutions to these challenges. For assessing large scale flow properties of basalt formation, we investigate whether various geochemical and geophysical datasets (e.g. Sr isotope profiles, electrical resistivity logs) can provide useful constraints. For assessing the influence of reactions on flow properties we describe our methodology of comparing state of the art reactive flow modeling with experimental results.

P10.8

A 3D shear wave velocity model from ambient noise surface wave tomography in the Helsinki area

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We employed ambient noise surface wave tomography (ANSWT) to construct a 3D shear wave velocity (V_s) model of the upper 8 km of the crust beneath the Helsinki metropolitan area. The study utilized data from three acquisition campaigns by the Institute of Seismology in 2016, 2018, and 2020, comprising a total of 260 seismic stations. These stations were deployed across a 40 km by 30 km area centered around the Aalto University campus, originally intended to monitor seismic activity associated with the Otaniemi deep geothermal system.

While the dataset was suboptimal for ANSWT due to variations in sensor types, digitizers, and heterogeneous station density, we successfully extracted meaningful information from fundamental Rayleigh and Love waves propagating between station pairs. We computed surface wave group velocity dispersion curves and mapped these curves onto 2D grids for each frequency. For each grid cell, we combined group velocities with averaged phase velocities to constrain 1D V_s models, assuming a five-layer parameterization. A neighborhood algorithm was then applied to invert for the 1D V_s models. Finally, the 3D model was assembled by aggregating the individual 1D models.

On average, the group velocity move-out pattern and its f - k phase velocity plots show that there is no dispersion. At the first order, it reflects a uniformity and homogeneity of the southern Fennoscandian shield with an average V_s of 3.4 km/s.

On the other hand, the 3D V_s model reveals vertical and lateral variations. In the south and south-east parts of the Helsinki metropolitan area, the model shows a velocity inversion between 1.5 km and 2.5 km where an upper layer has a 5 to 10% higher velocity compared to the lower one. This feature is in adequation with a vertical seismic profile done below the Aalto University Campus (Leonhardt et al. 2021). In the north and north-west parts, velocity increases with depth. The discontinuity between those two features appears just south of the Porkkala-Mäntsälä fault. At shallower depth, above 1000 m, we can see lateral variations of velocities where higher velocities seem to correspond to gneiss and granodiorite, while lower velocities with granite.

The study presented here demonstrates the applicability of ambient noise 3D seismic tomography as a tool to provide information about bedrock in an urban area, where most geophysical imaging techniques struggle because of noise condition.

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P10.9

MUSS25 survey in Mulliköräme, Finland: seismic imaging supporting base metal exploration

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Mining in the Pyhäsalmi area in Finland commenced in the 1950s, and the district hosted the deepest mine in Europe until 2022, with mining taking place below a depth of 1500 m. Despite the closure of the Pyhäsalmi mine, the region still holds significant potential for discovering new volcanogenic massive sulfide deposits, which motivated the seismic survey in the summer of 2025 in the nearby Mulliköräme area. The Mulliköräme mine was operational from 1989 to 2000 and produced 1.2 million tons of ore, with 6.08% zinc, 0.30% copper, and 17.05% sulfur.

Heinonen et al. (2012) showed that acoustic impedance differences between mafic and felsic rocks support detectable reflections based on seismic velocities and densities measured with drill hole logging. In the interpretation and 3D modeling of the previous seismic reflection profiles acquired mainly along the roads in the area, mapping this contact over large volumes has provided tools for deep mineral exploration.

In 2025, we used approximately 500 3C geophones to study the bedrock structure in the vicinity of the closed Mulliköräme mine as part of the MUSS25 project. Terrain conditions in the survey location were challenging in many locations due to swamps and wetlands. Geophones were deployed along four profiles about 200 m apart from each other. The profiles were oriented approximately in an east-west direction over mainly felsic, intermediate, and mafic volcanic stratigraphy. The northernmost profile was 2.5 km long with a geophone spacing of 10 m, while the other three profiles were each 1 km long with a geophone spacing of 15 m. Along the long profile, explosions were used as a seismic source at 20 m intervals with a dynamite charge size of 80 g. Additionally, ditches cutting the profiles at about a 45-degree angle were utilized to set explosives, and a 500 kg weight drop mounted on a Bobcat was used along roads as a seismic source. Thus, this acquisition resulted in a sparse and irregular 3D seismic dataset additionally to a profile.

The novel 3C seismic dataset will be used to retrieve seismic reflectivity along a geological profile previously interpreted by Kontkanen (2024). We will test how well seismic reflectivity and seismic velocities retrieved from refraction modeling replicate the interpretation of alteration and chemostratigraphy. The novel data will be integrated into the existing 3D models of the area, with the aim of providing new information for exploration.

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O11.1

Decade of Innovation: From Seismic Targeting to Discovery at Blötberget

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Blötberget iron-oxide deposits in central Sweden have been the focus of a decade-long research and development initiatives, not only for testing innovative exploration solutions but also unlocking deeper resources at depth. Beginning in 2015, a seismic landstreamer and drone-magnetic survey targeted the mineralization, demonstrating strong potential for technology testing (Malehmir et al. 2017a, 2017b). Subsequent downhole logging and physical property measurements confirmed that the mineralization should generate a strong seismic response.

Since 2016, multiple 2D and 3D seismic surveys have been conducted in the area. The pioneering 3D seismic survey in Sweden not only imaged the known mineralization but also indicated a downdip and lateral continuation (Malehmir et al. 2021). Earlier 2025, a collaborative effort within the Smart Exploration Research Center (SERC) led to the intersection of massive hematite-rich zones at approximately 1000 m depth, with iron content between 45-65% and densities up to 4900 kg/m³. This successful deep targeting validates the capability of reflection seismic methods to guide deep drilling programs. We will present the datasets leading to this discovery and illustrate the underlying physical properties responsible for the strong seismic signature. Furthermore, the borehole is equipped with a fiber-optic cable and will soon undergo a surface-downhole distributed acoustic sensing (DAS) survey, highlighting ongoing innovative solution testing and development at the site.

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O11.2

Subsurface Intelligence: Multiscale Geophysics and Advanced Analytics for the Energy Transition

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The accelerating demand for secure, sustainable, and low-carbon energy highlights the need for new approaches in subsurface exploration and monitoring. Geophysics, spanning airborne, land-based, and borehole methods, provides a unique capacity to characterize the Earth's structure and resources at multiple scales. In this contribution, we demonstrate how combining multi-platform geophysical surveys with advanced data analytics strengthens our ability to address challenges in the energy transition, including geothermal development, critical raw material exploration, and subsurface energy storage. Airborne techniques allow for rapid regional mapping of geological domains, supporting the identification of prospective zones for further investigation. Land-based surveys (gravity, magnetics, seismic, and electromagnetic methods) provide high-resolution imaging of lithological boundaries, structural features, and fluid pathways essential for site selection. Borehole geophysics, in turn, delivers ground-truth calibration and continuous subsurface profiling, ensuring the reliability of extrapolations from surface and airborne datasets. The integration of these methods is increasingly enhanced through modern data analytics, including machine learning, inversion frameworks, and multi-sensor data fusion. These approaches enable the extraction of subtle signals, reduction of uncertainty, and more robust predictive modelling of subsurface processes. Case studies highlight how this integrative approach facilitates risk reduction in geothermal resource assessments, improves targeting of critical mineral deposits, and supports the safe deployment of underground hydrogen storage and carbon capture projects. The results underline that geophysics, when combined with advanced analytics, is indispensable in guiding sustainable resource development and ensuring resilience during the ongoing energy transition.

O11.3

DESMEX: 3D inversion of SAEM and AFMAG data for mineral exploration on local to regional scales

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Electromagnetic (EM) methods are sensitive for changes of the electrical conductivity and therefore indispensable for the investigation of mineral systems, groundwater and hydrothermal resources. In the past years, the DESMEX consortium performed multiple large-scale Helicopter- and UAV-based semi-airborne EM (SAEM) as well as natural-source airborne AFMAG surveys for mineral exploration worldwide (e.g., Becken et al. 2020; Kotowski et al. 2025). SAEM measurements provide good signal-to-noise characteristics due to the installation of long, grounded transmitters at the surface, while the AFMAG method can cover larger areas in regions with strong natural-source signals and low infrastructure noise.

Inverting the corresponding data to obtain reliable subsurface conductivity models for complex 3D survey geometries and thousands of electric and magnetic field recordings requires a robust and flexible inversion framework, e.g., the open-source tools *custEM/pyGIMLi* (Rochlitz et al. 2023). In the western Harz mountains, a very large helicopter-based SAEM setup allowed to invert a regional resistivity model down to 1000 m depth in an area of more than 100 km². UAV-based SAEM exploration was carried out with two sensor types, a scalar and a vector magnetometer with complementary frequency ranges, to explore the extent of the Kropfmühl graphite deposit (Germany), the Hope (Namibia) and the Poderosa (Spain) massive-sulfide deposits on local scales. Combined 3D inversion of ZTEM and QAMT data from lake Hatchet shows great potential of the AFMAG method for regional-scale exploration.

The recovered conductivity models fit well with geological, borehole and additional geophysical data. Next to logistical characteristics, our results help to identify specific advantages and drawbacks of the applied methods and combining multiple EM (and other) methods for mineral or groundwater exploration across scales. In this context, the comparatively novel instruments, measurement setups and data analysis techniques developed in the DESMEX project exhibit a great potential for applications on a commercial scale.

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O11.4

Artificial Smoker: Geophysical characterization of an ultraslow ridge system for sustainable resource management

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Hydrothermal circulation is a fundamental Earth process that transfers elements and minerals from the crust and mantle to the oceans. This circulation commonly occurs along tectonic plate boundaries in the oceans, where heat sources are located at relatively shallow depths (~2–3 km). Cold seawater percolates downward, becomes heated, and is enriched with minerals from the host rock and magmatic volatiles. The resulting hot fluids (exceeding 300°C) rise buoyantly and are expelled into the ocean through chimney-like structures on the seafloor, commonly referred to as "Black Smokers." The ejected particles settle on the seafloor, forming rich mineral deposits known as "Seafloor Massive Sulfide" (SMS) deposits, making mid-ocean ridges highly attractive for meeting future mineral demands. Moreover, ridge settings hold significant potential for geothermal energy, white hydrogen production, and other valuable resources. However, harnessing these resources requires a thorough understanding of the complex hydrothermal systems to develop sustainable resource management strategies. Hydrothermal venting sites are widespread along the mid-ocean ridge system, occurring at all spreading rates and across diverse geological settings. However, the mechanisms driving hydrothermal processes vary depending on factors such as the presence of magma bodies, permeable zones, tectonic activity, and temperature. At ultraslow spreading ridges, where spreading rates are less than 20 mm/yr—such as the Southwest Indian Ridge, Mohns Ridge, and Knipovich Ridge—tectonic processes dominate over magmatic activity, resulting in the exhumation of ultramafic material to the seafloor along large-scale detachment faults. In this study, we developed two-dimensional, high-resolution velocity models through the crust and uppermost mantle of the Southwest Indian Ridge using wide-angle ocean-bottom seismic data. We present two ~150 km-long, high-resolution P-wave velocity models orthogonal to each other, running across and along the ridge axis at 64°30'E. We employed a state-of-the-art imaging technique known as full waveform inversion (FWI) using data from 32 ocean-bottom seismometers positioned along the two profiles. FWI is a data-fitting method in which the forward operator iteratively predicts the observed data by backpropagating the misfits to update the velocity model, thereby producing higher-resolution images of the subsurface. Based on our high-resolution velocity models, we observe finer patterns of velocity anomalies compared to traveltimes models, revealing more detailed variations in the degree of fluid-rock interaction. The high-resolution velocity models support the assessment of the feasibility of "Artificial Smoker," which replicates natural smokers, for the environmentally sustainable extraction of minerals, white hydrogen, and geothermal resources.

O11.5

Imaging the hidden part of the 2.5-2.4 Ga Koillismaa Layered Intrusion Complex with 3D seismics

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The Koillismaa–Näränkävää Layered Intrusion Complex (KLIC) (NE Finland) belongs to the group of 2.5-2.4 Ga mafic-ultramafic layered intrusions in Fennoscandian shield, which hosts several polymetallic deposits. The concealed part of KLIC, so called Koillismaa Deep Intrusion (KDI), manifests itself in form of ca. 50-km long gravity anomaly, which was investigated by GTK in 2020 by a 1.7 km long diamond drillhole where ultramafic rocks (pyroxenite, peridotite) were found at the depth of 1.5 km.

KDI was selected as a test area for the ERA-MIN SEEMS DEEP project, integrating electromagnetics, magnetotellurics and seismic methods. Project included acquisition of a pioneering ~22 km² 3D seismic survey, which is one of the first 3D seismic investigations of a deep layered intrusion and its feeder system. Despite the challenging terrain conditions with large and wet swamps, 2866 receivers were distributed altogether along 21 receiver lines (240 m interval) with 30 m spacing. A single nimble node with piezoelectric sensor (Stryde) was deployed at each receiver position. 22-tone Vibroseis truck was used as a source with 20 s long sweep between 20-160 Hz. A total of 1615 Vibroseis points were located along the forest paths and gravel roads with nominal spacing of 30 m.

The acquired data quality is very good with distinct first-arrivals beyond 5 km offset and reflections visible in the raw shot gathers. Data processing and imaging was performed up to pre-stack time migration. Final 3D seismic volume reveals a complex internal architecture of the KDI characterized by coherent reflectivity patterns indicative of modal layering as supported by petrophysical measurements and synthetic modelling. Interpretation suggests that the KDI is not a simple feeder but a more developed, conolitic or funnel-tube-shaped intrusion. Integration of seismic data interpretation with gravity inversion and geological data resulted in a model of the KDI, which successfully reproduces the observed gravity anomaly. A major thrust fault, likely associated with the Oulujärvi Shear Zone, was imaged for the first time, offering new insights into the tectonic evolution and mineralization potential of the region. This study highlights the advances in 3D seismic methods in hardrock environment and establishes a methodological framework for future mineral exploration in similar geological settings.

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O11.6

Integrating Physical Property Studies with Seismic Methods for Mineral Exploration: Examples from Sweden

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Although Sweden has some good database for physical properties of rocks such as density and magnetic susceptibility, there is no systematic information on seismic velocities but also electrical resistivity of rocks and minerals. These are fundamental because, together with density, they for example control the seismic response of rocks and thus the reflectivity of various geological entities and mineralized zones. Having such a database, built from surface and core samples as well as downhole sonic logging, would improve understanding of mineralization response in seismic data. The present study highlights the value of such data for designing seismic surveys for mineral exploration with case examples from Blötberget, an iron-oxide mineralization, and Bergby, an LCT-type granitic pegmatite system.

The Blötberget historical mine site served as a testbed for many different reflection seismic acquisition setups, from 2D to sparse 3D (e.g., Malehmir et al. 2021). Initially, most of these surveys focused on P-wavefield imaging of the main iron-oxide mineralization. For the first time, a multicomponent seismic survey was conducted at the site, motivated by the results from S-wave sonic velocities and the calculated S-wave impedances from downhole-logged boreholes. The S-wave impedance shows outstanding values for the mineralization horizons compared to their host rocks, implying that, where conditions are favorable, strong shear-wave reflections and/or diffraction can be generated from the mineralization (Markovic et al. 2025).

At Bergby, physical property data were collected from several outcrops. In situ measurements of P-wave velocity and magnetic susceptibility were performed directly in the field, while densities were determined in the laboratory on collected samples. The results show that pegmatite samples generally exhibit lower velocities, densities, and magnetic susceptibilities compared to their mafic country rocks. These contrasts for example suggest that pegmatite bodies may produce a seismic response but likely weak so that high-quality, high-fold, data acquisition should be aimed at.

These examples demonstrate how physical property studies, from downhole sonic logging to surface-based field measurements, can provide valuable information for the feasibility and acquisition design of seismic methods in mineral exploration.

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O11.7

Mapping lithospheric controls on mineral systems using continent-scale conductivity imaging

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Electrical conductivity is a powerful geophysical proxy for the subsurface processes that govern mineral systems. The emergence of continent-scale Magnetotelluric (MT) surveys now enables these controls to be mapped coherently from the upper crust into the asthenosphere. We developed a novel 3-D multi-scale MT imaging tool applied to two landmark datasets – the full MT USArray across the contiguous United States and the AusLAMP array of Australia – to image the electrical conductivity of the lithosphere of these regions. These models reveal conductivity signatures and gradients associated with cratonic margins, deep basins, active faults, as well as magmatic and metasomatic processes. Comparisons with the distribution of known deposits, seismic velocities, gravity, and heat-flow patterns demonstrate that electrical conductivity is a predictor of ore-forming settings. These results establish large-scale MT, combined with multi-scale 3-D inversion, as a key component for integrated lithospheric imaging and mineral potential mapping.

O11.8

From ground to skies – Geophysical investigation of Otanmäki mine site in UOMARI project

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The Otanmäki mine, located in Kajaani, Finland, was originally active between 1953 and 1985, producing vanadium, ilmenite, and iron ore. After its closure, the site remained dormant, with significant tailings and infrastructure left behind. In recent years, Otanmäki Mine Oy has initiated efforts to reopen the mine, leveraging historical data and circular economy principles. Collaborating with the Geological Survey of Finland (GTK), Otanmäki Mine Oy has conducted testing and beneficiation trials, achieving promising yields and market-grade quality (GTK webpage). Investigations continue under the UOMARI project (11/2023–3/2026), led by GTK and funded by the European Regional Development Fund (ERDF).

Geophysical investigations in Otanmäki include ground penetrating radar (GPR), electromagnetic (TEM and FEM), and magnetic methods across the mine area. In the tailings area, dielectric and resistivity values have also been measured.

GPR surveys in December 2023 used a snowmobile-pulled sled with radar unit, collecting over 15 km of data. Frequencies of 100 MHz were used in tailings and settling pond, 200 MHz over dams, and dual-frequency 300/800 MHz radar was manually pulled. In 2025, drone-GPR systems operating at 100 MHz and 1000 MHz revisited the area. Drill holes to the bottom of tailings sand were used to calibrate relative dielectric constant as $\epsilon = 6$, consistent with literature (Saarenketo 2006). Results show 100 MHz detected the bottom of tailings and settling pond, 200 MHz revealed dam structures, and 1000 MHz detected ice thickness. Separate laboratory tests on GPR signal attenuation with increasing water conductivity were also conducted and suggest a practical measurement limit around 1 mS/cm.

FEM measurements in March 2025 used a snowmobile-pulled sled with GEM-2 unit, operated at multiple frequencies. Due to limited depth penetration, a tTEM survey with an 8 m² transmitter and receiver pulled by ATV was conducted in September 2025. Preliminary data shows many negative time gates, suggesting IP phenomenon in the tailings area, as also documented in other studies (Bastani et al. 2025).

Magnetic survey in September 2025 used a GSM-19 magnetometer and Scintrex ENVI base station. After correcting for time variation, data was inverted to a 3D susceptibility voxel, revealing distinct structures. Interpretation is ongoing.

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O11.9

BABEL lithospheric seismic transect across a mineral-endowed Archean-Paleoproterozoic boundary

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Deep seismic reflection profiling has advanced our understanding of Precambrian orogenic belts by imaging crustal and mantle structures, providing direct evidence for ancient convergence and collisional processes. As part of the BABEL Project (Baltic and Bothnian Echoes from the Lithosphere), 2,268 km of deep seismic near-vertical reflection and wide-angle refraction data were acquired across the Baltic Sea and Gulf of Bothnia in 1989 (BABEL Working Group 1990). The present study focuses on BABEL lines 2–4 from the Bothnian Bay, located between the Skellefte and Vihanti-Pyhäsalmi volcanic-hosted massive sulphide belts. The original processing highlighted a prominent upper-mantle set of reflectivity, dipping towards the north and offsetting the Moho by 5–10 km, which was interpreted as a fossil subducting slab, supporting plate tectonic processes in the early Paleoproterozoic. These invaluable legacy data have now been reprocessed with state-of-the-art methods not available at the time, including advanced multiple attenuation and curvelet denoising, with a particular focus on improving upper-mantle imaging.

The reprocessing has substantially enhanced the imaging by resolving numerous individual reflection and diffraction events throughout the upper and the middle crust. The Moho boundary is now mapped with greater clarity and definition, and sub-Moho reflections can be traced down to 20 s (65–70 km depth). The results refine the geometry of the relict subduction, imaged as two narrow bands of north-dipping upper mantle reflectivity. Worth highlighting and new, the reprocessing work also revealed a south-dipping reflectivity to the upper mantle beneath the Archean-Paleoproterozoic boundary that has not been given attention before. We interpret this as a Paleoproterozoic suture zone, likely older than the subduction, and spatially associated with the Pajala shear zone, which may, for example, explain some of the Cr deposits observed at the surface.

Our findings suggest two oppositely dipping lithospheric structures, each previously inferred from surface isotopic signatures but not shown together in a single seismic image. When combined with crustal reflectivity interpreted as reworked Archean rocks, these results allow us to better constrain their contact with Paleoproterozoic rocks in the subsurface along a 200 km transect and relate them to major mineral systems in the region.

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O11.10

Ore forming processes of Ni-Cu-PGE-endowed mafic intrusions in central Sweden

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Ultramafic and mafic igneous rocks commonly host world-class Ni-Cu-PGE deposits. These endowed rocks are also present in the Bergslagen region of central Sweden. The Granmuren Ni-Cu-Co deposit, hosted by gabbro west of the historic mining town of Sala, was first identified in 2012 through core drilling of an anomaly detected in an airborne versatile time-domain electromagnetic (VTEM) survey. Since 2021, Ragnar exploration has advanced from shallow to deeper targets, leading to discoveries and refined constraints on deposit models and the geological controls of the sulphide system. However, little is known about the larger-scale ore-forming systems, highlighting the need for novel strategies to image the deep subsurface structures in the area and for improved, cost-effective, deeper targeting.

Ongoing studies integrate geophysics with structural mapping, age, and composition to design a seismic survey aimed at imaging these ore-forming systems. In the Sala area, several steeply WSW-dipping deformation zones define the western boundary of the felsic metavolcanic inlier (Ripa et al. 2002). To the east, simple, undeformed granites intrude metatonalites and granodiorites, whereas to the west, mafic intrusions are common, together with clastic metasedimentary and felsic metaintrusive rocks. These rocks have undergone, to varying extents, several episodes of ductile deformation and amphibolite facies metamorphism (Stephens et al. 2009). Importantly, the mafic intrusions have sufficient petrophysical property contrasts with the surrounding rocks to be detectable using seismic methods. We use complementary potential field methods and physical properties to model the key geological units in 3D, thereby providing the best illumination angle for the seismic survey. Building on more than three decades of hardrock seismic exploration experience (e.g., Malehmir et al. 2021), the survey will use novel acquisition strategies to overcome target illumination and logistical challenges in the difficult terrain of the mining district.

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P11.1

Electrical conductivity of 3D printed synthetic rocks with variable graphite concentration and distribution

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The transition to green energy has increased demand for critical minerals, such as graphite, vital in the production of e.g. batteries, mobile phones and other electronics (Reich & Simon 2024). Natural graphite is renowned for its low density and high electrical conductivity, appearing in nature as strong geophysical anomalies (e.g., Kukkonen 1984). However, the interpretations of geophysical anomalies are complicated by the non-uniqueness of potential field source distributions.

To ensure demands are met, it is essential to optimize mineral exploration through the development of new methods and improved scientific understanding. This study explores a novel approach to integrating 3D printing technology, otherwise relatively new in geosciences (e.g., Ishutov et al. 2018), into geophysics. A novel large-particle graphite-rich filament was produced and 3D printed into synthetic rock samples analogous to natural graphite-bearing rocks. The relationship between graphite concentration and electrical conductivity was investigated through petrophysical measurements.

Results show a clear positive correlation between graphite concentration and electrical conductivity. The conductivity of the printed samples falls within the lower range of natural graphite-bearing rocks, likely because the synthetic samples lack sulphides, which are proposed to enhance the bulk electrical properties of sulphide-bearing graphitic rocks (e.g., Loukola-Ruskeeniemi et al. 2023). Another explanation might be lower connectivity between the graphite flakes and pore structures in the printed samples.

Despite these limitations, this research demonstrates the feasibility of using 3D printing to produce synthetic geological analogues tailored to specific research needs. With further development, 3D printing may provide useful assistance in linking minerals' petrophysical properties to crustal phenomena, thereby supporting mineral exploration.

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P11.2

Combining two exploration methods in one with Seismic-While-Drilling in Blötberget, Sweden

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The Blötberget iron-oxide deposit, located in the mineral-endowed Bergslagen district of central Sweden, has been the focus of several geophysical investigations in recent years. Among these, a series of seismic surveys have aimed to delineate the lateral and vertical extent of the deposits while testing various methodological and technological approaches. The ore at Blötberget is a Kiruna-type deposit and primarily consists of high-grade iron oxides, magnetite and hematite, partly enriched with apatite. The mineralization occurs in 10–30 m thick sheets, dipping approximately 45° eastward along an NE-SW trending zone.

In early 2025, a scientific exploration borehole was drilled to verify the continuation of the ore body at a depth of 1 km, following its seismic imaging from previous surveys. During the drilling, a surface seismic array comprising 300 vertical-component and 12 three-component recorders was deployed around the drill rig for 45 days to enable Seismic-While-Drilling (SWD) measurements. SWD is a technique that records the seismic energy generated by the drill bit, which is subsequently processed to extract subsurface geological information.

This study explores the feasibility of retrieving reflections from the ore body captured within the SWD wavefield to image the mineralization ahead of the drill bit. Short time windows of the continuous drill-bit signal recorded by the surface array are cross-correlated with a pilot signal recorded near the rig to generate SWD seismograms. These correlated traces are then stacked to enhance the signal-to-noise ratio. The process is repeated for multiple drill-bit depth intervals, and the resulting datasets are processed using reflection seismic imaging techniques.

This study presents how seismic energy generated during drilling can be repurposed as an additional exploration tool, complementing conventional drilling and coring by providing imaging of mineralized zones ahead of the bit.

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P11.3

UNDERCOVER: A multi-scale approach for exploring mineral systems – First insights from an electromagnetic perspective on the Kuusamo Schist Belt, Part B – Ground-based EM

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The electrical conductivity is an important physical property for the investigation of mineral systems. It is sensitive to conductive ores as well as geological structures (e.g. fluid pathways). Combining various electromagnetic (EM) methods, we are able to investigate the geoelectrical characteristics of a mineral system at different scales and depths.

The Kuusamo Schist Belt (KSB) is a Paleoproterozoic orogenic belt in the Fennoscandian Shield and known for hosting polymetallic deposits at shallow depth and featuring high amounts of Au and Co (Leväniemi et al. 2024). However, the formation mechanism remains poorly understood.

Within the UNDERCOVER project, we aim for a multi-scale data set of various EM methods to resolve the greater picture of the KSB mineral system as well as showcase the EM-driven deposit-scale investigation at Juomasuo, the largest known Au-Co-Cu-REE occurrence in the KSB (Davies et al. 2025).

Accompanied by other geoscientific methods, the project covers the entire range from a large-scale magnetotelluric-array to a high-resolution controlled-source EM data set across the deposit. We present first insights from the 2025s field campaigns.

Part B: In May to July 2025, we acquired magnetotelluric data at over 200 stations across the entire orogenic belt and adjacent blocks. Initial data analysis shows excellent data quality and indicates dominant crustal-scale geological structures. The field work will be continued in 2026 increasing resolution of the magnetotelluric array to a 5 km site spacing. This array is designed to study the major tectonic structures at upper to mid-crustal scale.

Additionally, in September 2025, we completed a controlled-source EM survey including the investigation of induced polarization effects. We set up 110 electric field recorders on a regular grid with 250 m receiver site spacing and sequentially injected currents at 80 grounded electric dipole transmitters. The data set provides a dense coverage of the Juomasuo and Hangaslampi deposits. With this data set, we aim to image the upper 500 m with high resolution.

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P11.4

UNDERCOVER: A multi-scale approach for exploring mineral systems – First insights from an electromagnetic perspective on the Kuusamo Schist Belt, Part A – Airborne data

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Accompanied by other geoscientific methods, the project covers the entire range from a large-scale magnetotelluric-array to a high-resolution controlled-source EM data set across the deposit. We present first insights from the 2025s field campaigns.

Part A: We show two airborne EM data sets that were acquired in August 2025 using Supracon's QAMT airborne platform (Stolz et al. 2022). Airborne natural-source EM data were collected on a 1600 km² area using a regional grid with 1 km line spacing. The area spreads across the majority of the known occurrences. We aim for a model depth of 2 km.

On a more local scale, semi-airborne EM flights were also performed with the QAMT system over the Juomasuo deposit. The method combines powerful, grounded electric dipole transmitters with an airborne high sensitivity receiver and provides a higher spatial resolution (250 m line spacing) and up to 1 km depth of investigation.

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P11.5

Renewing petrophysical infrastructure: A next-generation magnetic susceptibility instrument for mineral exploration

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The growing demand for critical raw materials requires advanced exploration methods that integrate geology, geophysics, and mineral systems research system (McCuaig & Hronsky, 2014). Petrophysical data are a key component in this workflow, linking geophysical anomalies to rock properties crust (e.g., Clark 1997; Dentith et al. 2020; Enkin et al. 2020). However, much of the existing instrumentation in Finland and some other Nordic countries dates back to the 1970s (Puranen & Puranen 1977; Puranen et al. 1993a, 1993b) and no longer meets modern stability.

We present a newly developed petrophysical instrument designed and built at the University of Helsinki in collaboration with GTK, with development supported by the K.H. Renlund Foundation. The prototype kappabridge provides high-precision magnetic susceptibility measurements across a frequency range, enabling improved identification of diagnostic magnetic minerals such as monoclinic pyrrhotite abundant for example in volcanic massive sulphide deposits. The instrument is equipped with modern, high-quality electronics and a novel software package, ensuring improved accuracy, reproducibility, and compatibility with existing geological databases. Initial calibration and test measurements on reference samples from the Fennoscandian Shield demonstrate excellent performance, with high sensitivity. Especially, the frequency-dependent susceptibility capability opens new avenues for mineralogical discrimination in exploration settings.

This development represents an important step in renewing Finland's petrophysical infrastructure and contributes to the establishment of a nationwide petrophysical laboratory network, fostering interoperability, FAIR data practices, and integration with EPOS-ERIC Multiscale Laboratories. The new instrument strengthens the role of petrophysics in critical raw materials research and provides a foundation for future innovations in mineral exploration.

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O12.1

Involving First-Year Geology Students in Research activities: A CURE Light project

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As a first encounter with geosciences, introductory courses play a critical role in shaping students' motivation, engagement, sense of belonging, and their ability to envision themselves as future geoscientists. These factors are crucial for student retention. This project, "Involving First-Year Students in Research Activities: A CURE Light Project," aims to introduce first-year undergraduate geology students to authentic geoscientific research activities through a simplified version of Course-Based Undergraduate Research Experiences (CURE). In traditional CURE models, students independently identify research questions, collect data, and draw conclusions. This approach differs from conventional lab training, where educators design experiments and know the expected outcomes. While the incorporation of full-scale CURE can be challenging as they demand considerable time and effort from both students and educators, can be costly, and are often difficult to implement in existing courses, we aim to demonstrate that a lighter approach can yield significant pedagogical benefits. In teams of three, participating students engage in sample preparation, lab work, and data analysis, ultimately presenting their findings. This hands-on experience allows students to trace a rock sample through the geoscientific research process, enhancing their understanding of the subject's relevance and potentially igniting interest in scientific careers.

The project stems from the observation that a strong sense of belonging enhances motivation and engagement among first-year students. By working alongside technical and scientific staff, we seek to determine if hands-on research participation boosts students' perceived career prospects and strengthens their connection to the department. Our target group includes 35 first-year geology students enrolled in GEO1110, Earth Processes, in Spring 2025.

Our focus is on introducing students to diverse research tasks and the working life within geosciences, rather than extensive practical skills training. We collect qualitative and quantitative feedback through pre- and post-activity questionnaires to assess the impact of their research experiences on their sense of belonging, motivation, and interest in the field. Insights from this pilot project will guide the development of similar initiatives and contribute to the evolution of undergraduate geoscience education practices at the department.

O12.2

The “Finnish Phenomenon” of Geoscience Higher Education

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The declining popularity of geosciences in higher education (HE) globally has raised concern about an emerging skills gap in the field. Graduations, enrolments, and applicant numbers have declined 20 to 40% in many geoscience programs since 2013. These trends tend to be attributed to the negative public perception of geosciences in relation to environmental and climate change, a general lack of awareness about societal relevance of the field, and shifts in local labour market demand. However, the opposite trend has been observed in Finland over the past eight years as degree programmes in geology or geosciences have experienced a total increase of ca. 70% both in applicant numbers and enrolment. This contribution explores admission and application statistics and some of the activities and changes in the Finnish geoscience HE processes during the past ca. 10 years that could explain what the geoscience education community has come to call the “Finnish phenomenon”.

First, accessibility of the Finnish HE application process (joint application system) was improved in 2015 by transferring it to the digital Studyinfo.fi portal. However, neither overall national HE application statistics nor those from adjacent fields (e.g., geography and environmental sciences) since 2015 follow the same trend observed for geosciences. This most likely rules out application-system-level effects as the cause of the phenomenon. To further enhance the visibility of geosciences among potential applicants, a joint landing page for all geoscience degree programmes was established within the Studyinfo.fi portal in 2022.

Second, steps have been taken to address the fact that geoscience is not taught as a separate subject in Finnish upper secondary schools, which is a key factor affecting the perception of geosciences as a career and study choice among potential applicants. Since 2020, secondary school collaboration has been systematically improved especially at the University of Helsinki through a working group that includes staff, students, City of Helsinki education services, and schoolteachers. The visibility of geosciences in Finnish secondary schools has also been enhanced through the activities of the International Earth Science Olympiad (IESO) since 2018.

Third, one of the major joint efforts in the Finnish geoscience education community has been the FIN-GEO project funded by the Ministry of Education and Culture in 2021–2023. The FIN-GEO network significantly strengthened national cooperation in geoscience education and established permanent collaboration platforms within the community.

Finally, interest in geosciences as a vocation seems to be affected by traditional and social media exposure. In the past ten years Finnish geoscientists have increasingly served as experts in media coverage of diverse geoscientific topics and contributed to the field's visibility through popular science publications and geoscientific social media content aimed at prospective students

O12.3

Geoscience Olympiads as a Driver for Growth in Geoscience Education

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Around the world, geoscience programmes face declining enrolment despite urgent societal needs for expertise in climate change, natural-hazard mitigation and sustainable resources. Finland is an exception: interest in geoscience studies has grown in recent years. One contributing factor is the country's active participation in the International Earth Science Olympiad (IESO) — a global competition founded by the International Geoscience Education Organisation (IGEO) over 15 years ago. IESO is unique among science olympiads in combining rigorous written and practical tasks with international field and team investigations that foster cross-cultural scientific collaboration.

Finland first joined IESO in 2018 and has participated every year since, including during the pandemic's online editions. The Finnish Geological Society (SGS) coordinates a nationwide online preliminary contest for upper-secondary students; the top 16 attend a four-day residential training camp at research field station, taught by lecturers from the Universities of Helsinki and Åbo Akademi. The best four students form the national team, guided by professional geoscientists as mentors. Because geology is not a regular upper-secondary subject in Finland, the camp is essential in providing theoretical and field experience for the high-level Olympiad tasks.

IESO problems typically address energy resources, sustainable raw-material use and recycling, groundwater management, geohazards, environmental pollution and climate change. Success requires understanding Earth-system interactions, handling authentic data and communicating results effectively. The International Team Field Investigation (ITFI) and Earth System Project (ESP) strengthen inquiry skills and collaborative learning that are central to global sustainability science.

National participation brings clear educational benefits. The preliminary contest, training camp and media coverage raise awareness of geosciences among students, teachers and the wider public. Many participants report that the experience motivates them to pursue geoscience degrees. Finnish universities now recognise Olympiad achievement as an alternative admission pathway: students who reach the national team gain direct entry (once generally eligible) to the B.Sc. programme in Geosciences at the University of Helsinki and to geology at Åbo Akademi. Early evidence shows that this route is already contributing new talent to the field.

Recent reform of Finland's university entrance examinations, with one advanced section dedicated to geosciences, is expected to further raise the field's visibility and broaden the pool of applicants. Yet the Finnish experience also illustrates a wider point: targeted national support for IESO participation can link schools, universities and society, strengthen STEM pipelines and help secure the next generation of professionals needed to address pressing environmental and societal challenges.

O12.4

Evaluation of a Formative Feedback Tool in University STEM Education

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The quality of university education has been a topic of discussion for many years (see e.g. the reports by Fox & Hackerman (2003), Singer et al. (2012) and Kober (2014)). A very useful component in the optimization in learning outcomes of a course are evaluation and feedback by the students. Today, students often evaluate university courses, including STEM courses, by using summative feedback, e.g. by filling out a survey about the course content and teaching method at the end of the course. This type of feedback has several drawbacks and, therefore, has been criticized (e.g., Chen & Hoshower 2003). For example, summative feedback does not make it possible for the students to give feedback to the teacher about the course while the course is ongoing. As a result, communication about the course content and teaching methods between the teacher and students is not possible.

At the department of Geoscience of the University of Bergen (GEO), a formative course feedback tool has been developed as a way to promote feedback and communication between teacher and students. This tool, which is easy to use, consists of a small survey that is held regularly (e.g. weekly) throughout the duration of the course. The survey results are almost immediately available to the teacher and so can be used to address feedback by the students while the course is ongoing. Over the past two years at GEO the feedback tool has been used in numerous courses at all levels.

The survey tool will be shown, and we will explain how it is used. Furthermore, we present an analysis of the use of the survey tool for a number of courses at GEO. This analysis suggests that there is a correlation between the use of active learning in a course and the response rate of the survey. On the other hand, the survey response rate hardly depends on the class level, class size or topic. It also turns out that the instructors use the tool with varying frequency and in various ways. The latter includes using the survey specifically as a means to identify more challenging parts of the course and as a means to improve communication between the teacher and students about course content and teaching methods.

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O12.5

A National University Course on Geohazards in Norway

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Since 2020, a national university course on geohazards is taught in parallel at the Universities of Bergen, Oslo and Tromsø. A national consortium consisting of more than 30 experts of earth science and education has developed the course, which is continuously updated with new materials. The course gives an introduction to various types of geohazards, their potential consequences, and disaster risk management. Students learn about the geological and physical processes driving geohazards, how society is affected by and can cope with geohazards, and the mitigation measures that can be implemented to prevent disasters. Students thereby develop an understanding of the link between nature and society, and how this link affects the potential consequences of an event. The course focuses on student-active learning and it is taught through a series of thematical modules that are developed by the leading national experts for each theme. Most of the teaching takes place in “flipped classrooms”, where students familiarize themselves with the theoretical basis before class, and teaching time is spent on discussion and group activities. The flipped classrooms are supplemented with GIS-based exercises and an excursion where students can observe and identify geohazards and mitigation measures in the field. Assessment is based on a portfolio of individual and group assignments. We will present the key components of the course and discuss how our approach to teaching supports student learning. We will also address the benefits and challenges we have experienced in this national cooperation in teaching.

O12.6

Introduction to Python for Geographic Data Analysis: A new, open resource for teachers and learners

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The geosciences are among the many fields of science undergoing a transformation as massive digital datasets and powerful computational tools have become more widespread. While the potential of these tools is clear, their use requires skills that may not be part of university geoscience education and thus limit students' potential to benefit from these emerging tools and technologies. Taking full advantage of the possibilities provided by massive spatial and temporal datasets, artificial intelligence, and CPU and GPU supercomputing requires educational resources to develop the core skillset needed by modern researchers.

Introduction to Python for Geographic Data Analysis is a new textbook designed to introduce fundamental concepts for working with geospatial data from introductory Python programming to batch processing and visualization of vector and raster geospatial datasets. It is written assuming no prior experience with programming, and little to no experience with geospatial data. The first part of the book thus introduces the basics of programming using the Python language, how to work with tabular (spreadsheet-like) data using the **pandas** Python library, and how to produce static and interactive data visualizations. Part two covers geospatial essentials, working with vector and raster data, visualization of those data, and how to utilize online data sources. The third part of the book provides several case studies, demonstrating how to use what readers learn in the book in real-world applications. Finally, the appendices provide guidance on best practices for programming in Python and an introduction to version control.

The book is available as an open online resource at <https://pythongis.org> and soon to be available in print (check the book website for details). Teachers who would like to introduce students to programming and working with geospatial data may find this an appealing resource, as we have deliberately targeted geoscientists and geographers in the examples used in the text. Other learners may benefit from examples of how to use open-source libraries and Python programs to improve the efficiency, accessibility, and reproducibility of their science.

O12.7

Oulu Museum of Mineralogy & Geology 2.0 - Towards European Capital of Culture 2026

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In recent years, many mineralogical museums have been closed or moved to smaller premises (Kinnunen 2014). At the same time, photogrammetry and various augmented reality (AR) technologies have been developed. This has enabled institutions to develop virtual museums and collections, making it easier for museums to reach the public. (Apopei 2024) The aim of this study is to present the University of Oulu's Mineralogical and Geological Museum 2.0. The museum consists of physical samples and virtual 3D photogrammetric models combined with XR (Mixed reality) technologies.

Since 2024, geological and mineralogical samples from the University of Oulu have been actively virtualized. The collection also includes outcrop models from various parts of Northern Ostrobothnia and Europe. The collection comprises a total of ~700 virtual rock, mineral, and outcrop models. The museum's collection has also been supplemented with high-resolution images of mineral samples.

The virtual models are part of the Oulu European Capital of Culture event. Thanks to this sub-event, everyone can learn about Finnish and Nordic geology from home without having to travel. The models also provide useful information for those who want to study rocks on site.

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P12.1

Motivation, Recruitment and Retention in Geoscience: A Two-wave Mixed-Methods Case Study at the University of Oslo

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This study investigates early motivations and student retention among first-year geoscience students at the University of Oslo using a mixed-methods design that foregrounds qualitative evidence. This study uses data from a workshop with approximately 48 first-semester students (an introductory event for peer formation and orientation), semi-structured interviews at programme start ($n = 17$) and after one year ($n = 12$), and an adapted Science Motivation Questionnaire administered at the same two time points. The analysis is framed by Social Cognitive Theory and Self-Determination Theory, where we use thematic coding to trace how motivational types and their drivers change over the first academic year. Qualitative findings show that initial entry into geoscience is often shaped by external influences such as parents, teachers and peers rather than by pure personal interest, and that fieldwork expectations and social connections are central attractors. Over one year motivations shift: many students move toward greater autonomy, personal growth and identification with the discipline, while career orientation remains a dominant motive. Further, we also find that grade-focused concerns increase under assessment pressures. Crucially, the institutional environment mediates these trajectories. Students embedded in supportive peer networks and in small, interactive teaching contexts report strengthened self-efficacy and sustained engagement, whereas students who experience peer dropout or limited teacher accessibility report isolation and higher withdrawal risk. Quantitative correlations between self-efficacy, intrinsic motivation and self-determination support these qualitative patterns. We recommend early structured peer mentoring, clearer and more transparent assessment and workload practices, and targeted career-pathway communication to stabilize career-driven motivation. Our findings have direct implications for teaching practice in geoscience and broader relevance for STEM recruitment and retention. We designed this project with the goal of easy extension to other faculties, with potential collaboration with UiO's Biology Department and the Department of Educational Science.

P12.2

Teaching environmental geology – challenges in academical and societal viewpoints of practical application in the learning process

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Montgomery (2014) express that “all of geology might in one way be regarded as environmental geology. But usually the term environmental geology primarily describe geology and how it directly relates to human activities, that also could be described as geology applied to living”. It could also be described as applied geology, natural hazards, pollution and waste-disposal etc. Important is that geoscience is central to many types of challenges we face today, in sustainable development and is crucial for environmental work.

There are several challenges when teaching environmental geology. On one hand there is the *theoretical* part with basic knowledge in many geoscience and the progress in research today, dealing with environmental geology issues. On the other hand there is a very *practical and applied part*, with ways to work and routines to follow when performing environmental geology. In different part of the working process, these two parts play different roles, depending on questions at hand, and sometimes they both interfere in the planning, performing, evaluation, interpretation etc. of environmental geology work. There is several other disciplines playing a central part of environmental issues and viewpoints, but it is obvious that geology is very central part in environmental work. For example in areas like sulphide bedrock, brown soils, emissions to air, soil quality, surface- and groundwater, deposition of pollutants in soils and sediments, risk analysis etc.

I present a solution from teaching environmental geology in master course (half semester course) at Gothenburg University, with two main tracks of learning following the whole course. On track is the theoretical and scientific research part, picking up both basic knowledge on subjects like sulphide bedrock and brown soils and bringing up current questions of in society like PFAS in soil and water. The other track is what I call “from wheat to bread”. This is the practical part of the course, built up as an environmental geology investigation of a site. In groups the students have to perform an investigation project from background, planning etc., to actual sampling, analyzing, and finally evaluating results. The investigation project ends with report and poster with oral presentation and explaining in “popular” and easy access text. The investigation must follow up the theoretical part, like in sampling strategy or choice of type of analysis, and also relate to handbooks and recommendations for performance and qualitative work in these situations from organisations and state authorities.

The outcome of the course is high quality work and presentations, in line with professional managed work. It is also very common that students from the course ends with practice and/or first professional work after studies, and sometimes already during the course.

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O13.1 (Keynote)

Bringing rocks to life – My journey in science communication

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According to the latest Eurobarometer, most people in the European Union have a positive attitude toward science and scientists (European Commission 2025). However, regarding the statement about whether scientists are open to engage with citizens, 49 percent responded “describes well”, while 40 percent responded “describes badly”. Interestingly, support for the statement that scientists are “bad at communicating” has overall slightly increased since 2021, but there are differences between countries: in Finland, support for this statement has declined since the last survey.

Science communication and the dissemination of research findings can significantly influence how science and research are perceived in our daily lives and enhance the overall understanding of the nature of the surrounding world. Scientists and other experts can inspire people to become interested in science, generate epiphanies, and even affect to politics and legislation.

My journey in science communication began while I was conducting my doctoral research over ten years ago. During that time, I created a blog titled “Mystery of the Greenstone” (“Vihreäkiven arvoitus” in Finnish), which not only provided me with an opportunity to communicate about my research and geology but also served as a playground for science communication. It allowed me to experiment with various approaches, including more creative methods such as writing science poems and food blog-style texts inspired by geology. I found my research topic and geology in general to be so fascinating that I wanted to share it with others.

Since then, I have, for example, written articles and given presentations to different audiences, engaged in projects that combine science and art, and authored a non-fiction book on the geology of Finland’s bedrock (Heinonen & Lehtonen 2024). Today, my motivation for science communication is also driven by a desire to take part into discussion related to social topics, such as the use of natural resources, and to highlight overlooked topics, like the role of women in the history of geology.

In this presentation, I will show examples from my own career and discuss the importance of science communication, particularly in the context of geology. I will also examine the potential of creativity and collaboration between the arts and sciences as well as address the significance of geoethics in science communication.

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O13.2

Geoscience outreach and communication in Lauhanvuori – Hämeenkanigas UNESCO Global Geopark, Finland

Pasi Talvitie

Lauhanvuori - Hämeenkanigas UNESCO Global Geopark, Kankaanpää, Finland

UNESCO Global Geoparks are single unified areas with internationally valuable geological sites and landscapes, and their mission is to promote geoscience learning, geotourism and sustainable development. There are five UNESCO Global Geoparks in Finland in 2025. Geoparks are part of the IGGP-program of UNESCO.

Lauhanvuori – Hämeenkanigas Geopark in Western Finland has been part of the UNESCO Global Geopark programme since 2020. The area covers ca. 5000km² and has ca. 40 000 inhabitants and covers land in ten municipalities in four provinces: Ostrobothnia, Pirkanmaa, Satakunta and Southern Ostrobothnia. The theme of Lauhanvuori – Hämeenkanigas Geopark is “From mountains to mires”.

There are 56 maintained geological sites in the geopark. Most of the sites are managed by Metsähallitus, Parks and Wildlife Finland, and some are managed by local municipalities and other organizations. The onsite interpretation in Lauhanvuori – Hämeenkanigas Geopark has been developed in co-operation with Metsähallitus. In addition to physical information panels, digital content, including videos, 3D-models and sound, can be accessed onsite through QR-codes.

Offsite interpretation in the Geopark is provided at information centres and information kiosks. Information centres are being developed and maintained by stakeholders, with the geopark providing materials, expertise and technical assistance. Smaller scale information kiosks have also been built in central public locations.

The geopark utilises various digital platforms for communication, of which many can be accessed through the geopark website (lhgeopark.fi). Social media is used for promotion of geoscience related subjects and geotourism. Videos and animations are an important tool for promoting geological themes in the area.

Cooperation with universities and schools is an important part of geopark operation. The Geopark provides assistance in arranging geoscience and geotourism related field courses and symposiums in the area. Schools in the area use geopark sites routinely for their outdoor education courses, and the connections between UNESCO Global Geoparks are utilised in arranging international courses. The Honkajoki gymnasium Geoeducation centre is actively developing new tools for earth science education.

The most important and rewarding means of geoscience communication is engaging people on site. Direct and frequent communication with non-specialists helps to mitigate the difficulties of communicating abstract subject matter to broader audiences. Geoscience communication needs not only geoscientists, but also storytellers, graphic artists, videographers, computer scientists and people with muscles, shovels and tools.

O13.3

Designing the interaction and outreach for a large, multidisciplinary flagship research initiative securing water for people and ecosystems by means of new digital solutions

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Digital Waters Flagship (DIWA) is a large Finnish research consortium consisting of 6 organizations. Our goal at DIWA is to secure water for people and ecosystems by implementing integrated and sustainable practices and new digital solutions. Together with the related PhD pilot programme, DIWA reaches almost up to 200 scientists working with various aspects of freshwater and the coastal zone. This includes 60 PhD researchers, who started their journey during the years 2024 and 2025. We explore the challenges and opportunities of designing the interaction and outreach events and channels for multidisciplinary staff, societal and business stakeholders, and the public, by means of podcasts, films, seminars, conferences, blogs, as well as field trips and workshops.

Our talk focuses on how to increase the knowledge of the young scientists regarding the common themes of the flagship and the more specialized fields of research to create meaningful collaboration, co-authorships, and discussions between the scientists. For example, we are using blogs written by our working groups, research themes, and PhD researchers as a means to increase mutual understanding of each research topic, as well as to provide written online material on our research using pre-identified keywords to increase our outreach online. We are also using film and podcast formats to boost our outreach to the public.

Field trips for the international PhD researchers are designed to support their understanding of the Finnish environment, the fluvial processes, and what type of seasonal variation and phenomena may impact their scientific data or, for example, the operating environment for automation and robotics solutions. The challenge here is producing educational content that is beneficial across the multiple fields of research that our scientists represent.

O13.4

Steinfluensing: How to Make Rocks Trend on Social Media

Gard L. Andersen

GeoloGard, Oslo, Norway. Department of Geosciences, University of Oslo, Oslo, Norway

Reaching audiences outside academia requires meeting people where they are. Today, much of that interaction happens on social media. In Norway, the so-called «science crisis» («*realfagskrisen*») is an ongoing concern, as fewer young people choose science-related studies. To show youth how exciting and relevant the natural sciences are, scientists need to be visible on social media.

For the past three years, I have been doing «*steinfluensing*» («rock influencing») on TikTok and Instagram. Under the outreach name *GeoloGard* (@geologard), I post short videos about Norway's geological history, building stones, and fieldwork. With more than one million video views on TikTok in 2025, I can confidently say: rocks can trend on social media.

In this presentation, I will share my experiences as a Norwegian-speaking content creator, including working with video and story formats, building an audience, and dealing with hate comments. I will also give practical advice for researchers who want to get started with social media outreach. By making the geosciences visible on platforms where young people already are, we can spark curiosity and show that geoscience is not only important – it is also really cool.

O13.5

Communicating about ancient Finnish volcanoes on social media: Harnessing the short video format

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Modern day volcanism often draws the attention of the general public, but many people in Finland do not realize that they are walking on volcanic rocks in their own backyard. Around 1.9 billion years ago, there was a volcanic island arc in southern Finland and outcrops of these rocks can be found in, for example, the Helsinki region.

Through a joint course between the Faculty of Science at the University of Helsinki and the journalism program at Haaga-Helia University of Applied Sciences called How to make a science video, we set out to make an educational video about ancient volcanism in southern Finland. This annual course is led by experienced science video producers and professionals in journalism. Participants in the course are placed in teams, comprised of both journalism students and scientists at different career stages. The aim of the course is to produce a fairly professional two-minute video suitable for platforms such as YouTube, and also one or two shorter teaser videos filmed with smartphones for social media channels such as Instagram. At the conclusion of the course, the two-minute videos by each team are published on the Youtube channels of both institutions.

In the process of making *The Search for Finnish Volcanoes*, our team learned to develop our initial idea into an achievable movie script, and execute this plan using a variety of techniques. The video includes clips filmed by the coast of Helsinki in freezing rain and wind, an interview with a local expert and author of a book on this topic (Heinonen & Lehtonen 2024) using green screen in the studio at the University of Helsinki, as well as an animation made by a close collaborator, showing the audience how the volcanic rocks formed.

In this presentation, we will highlight the processes of producing this scientific video, and share the resulting video.

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How to make a science video course blog: <https://blogs.helsinki.fi/science-video-course/>

O13.6

Communicating geodiversity across disciplinary and public boundaries: Reflections and strategies for enhanced geoscience outreach

Maija Toivanen

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As a geodiversity researcher working at the intersection of geography, geology, and ecology, I regularly encounter the challenge of communicating geodiversity concepts to diverse audiences - from researchers in different disciplines to the general public with varying environmental awareness and knowledge of field-specific topics and terminologies. This presentation reflects on these communication experiences and explores how insights from science communication research might improve geoscience outreach practices.

Drawing from my work in geodiversity research, I discuss the practical challenges of translating geodiversity concepts across disciplinary boundaries and various audiences. Through specific examples, I explore both successful communication moments and persistent challenges in bridging these knowledge gaps.

During my geodiversity-focused PhD journey, I also studied science communication. My master's thesis in science communication examining how researchers popularize their own work revealed that scientists employ diverse communication strategies, but often underutilize techniques that could enhance audience engagement and understanding (Toivanen 2024). I reflect on how these findings apply to geoscience communication, and how we might enhance our communication approaches for different audience needs and contexts.

This presentation aims to foster discussion about improving geoscience outreach by combining practical experience with communication research insights. Rather than prescriptive solutions, I propose questions and frameworks for more strategic, audience-aware science communication that can enhance public understanding of geosciences and their relevance especially in this era of environmental crises.

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O13.7

How Can Circular Mining Improve the Social License to Operate (SLO): Evidence from Circular Economy Literature in Mining

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The concept of circular mining is promoted to avoid the accumulation of liabilities while recovering the critical raw materials that helps to reposition the mining sector within green transition. This study synthesizes the findings from 51 studies on managerial aspects of mining. Moreover, it specifically addresses articles for circular strategies in mining that improve the Social License to Operate (SLO) with a special focus to re-mining and mining waste valorization. The results show that circular strategies are not treated uniformly across literature, instead it shows an evolution in responsible mining thinking of mining companies. A pyramid structure which is inspired through managerial maturity models has been created to represent responsible mining thinking evolution. It has identified that 45.1% of articles highlighted the pursuing of environmental and social responsibility through circular strategies like waste and tailing valorization, creating safe by-products, water purification and reuse which can be identified as the foundation stage. The guiding logic of this stage is to *“reduce liabilities and unlock value where ore grades fall”* and it is driven by higher disposal costs, declining head grades or regulatory pressure. Approximately 29.4% of articles account for second stage of the pyramid which discussed site-specific circularity and supply chain responsibility. They are showcasing the idea of *“creating shared value by collaborating beyond mine gates.”* The upper stage which is represented by 23.5% studies revealed ideas about corporate responsibility and mining closure where the companies focused on repurposing mines by linking with circular strategies to ensure the idea *“legacies support communities beyond linear extraction”*. As the aspirational stage of the pyramid, only 9.8% of articles reflect ethical responsibility. In this stage the mining firms acknowledge the limits of their circular integration by being transparent. Their commitment is *“not greenwashing and being honest about limits”*. This thinking progression of mining companies on mining waste valorization and re-mining provides evidence on how literature has been clustered across the levels of SLO under responsible mining. The pyramid concepts reveal how compliance-oriented/forced practices of mining companies evolved into their own ideas of ethical commitments. The major share of articles in foundational stage reflects that there is a dominance of policy and technology-oriented articles in the literature highlighting that the scholars are more enthusiastic on studies which use immediate and measurable variables. In contrast, very limited number of articles address ethical responsibility in circular mining that questions about the transparency on limits of circularity. This highlights that even though moral concepts are evident in literature, it is less frequently used in practice.

O13.8

Sociopolitical geology: Environmental activism, land use, corporate conduct and geoethics in mining and mineral exploration disputes in Finland

Toni Eerola

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The PhD thesis examines the social license to operate (SLO) within Finland's mining industry from a sociopolitical geology perspective. It comprises three articles that explore the mining-sceptical movement, mining and mineral exploration disputes (MMEDs), and the corporate conduct of companies engaged in mineral exploration. The study spans two decades of industry transformation, marked by the resurgence of foreign mining companies and the revitalization of the Finnish environmental movement since the mid-2000s. The articles employ mixed methods and are framed through the lenses of protest waves, SLO, and stakeholder theory. The thesis introduction adds a novel layer of spatial analysis by applying sociopolitical geology, geosystem services and geoethics to Finnish MMEDs. When as sociopolitical geology examines influence of geosystem services on human interests, geoethics observes corporate and activist conducts and their ethics in such context.

The Finnish mining-sceptical movement is conceptualized, and its evolution traced through three phases: the uranium debate, the mining debate, and the green energy transition. This progression is proposed to constitute the sixth wave of Finnish environmental protest, closely linked to the broader climate change discourse. The study also identifies parallels between this protest cycle and social movement (SM) theories, which span the formation of SMs to the emergence of protest cycles involving SMs and non-governmental organizations.

A key finding is that MMEDs in Finland are closely tied to land use in sensitive contexts, including the Sámi homeland, tourism destinations, regions with second homes, reindeer herding zones, groundwater reserves, nature conservation areas, and association with uranium. These disputes are often exacerbated by poor corporate conduct, particularly a lack of communication and stakeholder engagement, as well as reputational issues.

MMEDs frequently arise close to tourism destinations and in second home areas, driven by tourism entrepreneurs, tourists, and second homeowners. This phenomenon, termed '*not in my leisure area*' (NIMLA), is derived from '*not in my backyard*' (NIMBY) and reflects trans-local opposition from people who do not reside permanently in the affected areas.

The thesis also finds that corporate online communication regarding SLO, and the use of low-impact mineral exploration technologies (LIMET) often coincides with operations in these sensitive contexts and involvement in MMEDs. However, the adoption and promotion of LIMET appear primarily as strategies to enhance corporate image rather than genuine efforts to secure SLO.

The thesis introduction complements the articles by integrating new concepts into Finnish social science research on mining. The aim is to provide new insights into MMEDs and the mining-sceptical movement, thereby contributing to multidisciplinary research on the evolution of the mining debate in Finland.

O13.9

From critical minerals to critical questions: geoethics, responsibility, and outreach for a sustainable future

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Effective communication of geoscientific knowledge is increasingly vital as society navigates the challenges of energy transition. This responsibility is already widely recognized in our field. While geoscientists are central to identifying and extracting geological resources for this transition, our role in public dialogue and outreach is equally important.

The extraction and use of rare and valuable natural resources (where “valuable” refers not only to monetary worth) raise complex questions about environmental impact, societal priorities, and ethical responsibility. How much of these geological resources do we truly “need” for well-being and a sustainable future?

A key outreach message in these pivotal times could be the need to reflect on the ultimate purpose of resource use. While enabling the energy transition, many rare geological resources are also consumed by activities of questionable societal value, such as cryptocurrency mining and unnecessary AI operations. Addressing these issues requires transparent communication about environmental costs and societal trade-offs. Geoscientists can lead by example, advocating for moderation, responsible stewardship, and a shift away from the paradigm of endless growth toward more sustainable and equitable practices.

Even though we geoscientists may be among the most aware of the problems caused by climate change, pollution, and overconsumption, we often act as if these issues are not real. We still fly to conferences—even within our own countries—and our diets frequently include foods with high land and energy footprints. In many ways, our actions do not yet match our awareness. This, too, is unsustainable.

Integrating geoethics into our outreach means encouraging critical thinking about what constitutes true value and progress for both humanity and the planet. By sharing our understanding of how precious geological resources are, we can empower people to reserve them for purposes that genuinely improve our lives — both short- and long-term. We must be able to look beyond the current difficult geopolitical situation.

P13.1

Level Up Your Geoscience Outreach – Discover how the EGU Outreach Committee can support your communication journey

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The European Geoscience Union runs a substantial outreach programme, co-ordinated by the EGU Outreach Committee (OC).

The Aims of EGU OC:

- ☐ Increase public awareness of geoscientific research by EGU members.
- ☐ Facilitate the dissemination of information beyond the geoscience community.
- ☐ Highlight societal challenges that geoscientists can address.
- ☐ Strengthen links between scientists, policymakers, journalists, and the public.
- ☐ Train and support geoscientists in outreach, engagement, and science communication.

Key Target Groups

- ☐ EGU members and the wider geoscience community.
- ☐ National and international geoscience societies, agencies, and enterprises.
- ☐ Non-geoscience institutions, organisations, and the public.
- ☐ Decision-makers, media professionals, and educators.

What the OC Offers

- ☐ **Communication Channels:** newsletters, websites, blogs, social media, and data portals & repositories to share research and information.
- ☐ **Training & Support:** outreach, public engagement, and science communication workshops, mentoring programme at the annual EGU General Assembly (GA).
- ☐ **Education and Outreach Sessions at the GA:** covering science communication, higher education, EDI (Equality, Diversity, and Inclusion), geoethics, open science, and policy.
- ☐ **Awards:**
 - ☐ *Katia & Maurice Krafft Award* (outreach & engagement)
 - ☐ *Angela Croome Award* (Earth, space, and planetary sciences journalism)
- ☐ **Funding Opportunities:**
 - ☐ *Teacher–Scientist Pairing Scheme:* up to €2000 per pair to co-create lesson plans and videos.
 - ☐ *Public Engagement Grants:* up to €2000 per grant for innovative outreach projects.
 - ☐ *Geoscience Days:* up to €10,000 to host public engagement events across Europe.
 - ☐ Funding to offer *Science Communication Workshops:* up to €3000 per online workshop
 - ☐ Science Journalism Fellowship: up to €5000 to enable reporters to follow scientists on location to report on ongoing research in the Earth, planetary or space sciences

The EGU Outreach Committee works closely with the EGU Equality, Diversity and Inclusion Committee and EGU Education Committee.

Want to get involved in the OC activities? Find out more: <https://www.egu.eu/outreach/> or contact us directly at: outreach@egu.eu.

P13.2

Antarctica – fascination of the extreme

Ane Karine Engvik

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Antarctica is the Earth's least explored continent - the continent surrounding the South Pole, the coldest, whitest and driest nature environment on Earth. Antarctica is the home of the world's largest ice sheet, the oldest preserved ice, the strongest winds, the southernmost active volcano and three billion years old rocks. Nearly no life can survive all-year around in this extreme environment, but some of the toughest young birds grow up in the unkind climate.

The discovery of this continent of ice started some hundred years ago, but the first wintering expedition was in 1898-1900. The south pole was reached in 1911, after a tough race between Amundsen and Scott. Today both exploration skiers and researchers visit and work in Antarctica.

The fascination of the extreme environment is the attraction of the book "Antarctica", written for children and youth. It gives non-fiction tales about nature and expeditions, including images and a dictionary. With the core of geoscience, combined with interdisciplinary nature stories, historical exploration and stories from today's expeditions, we aim reaching the new generations fascination for science and exploration. Antarctica is the world most vulnerable environment. To preserve the environment, we need exploration and mapping of the nature. Today the global community is managing this continent dedicated to peace, research and nature preservation together.

P13.3

From geological database to outreach – stories of Smøla (Western Norway)

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The community of Smøla is situated by the ocean along the western coast of Norway, a municipality covering their own groups of islands. Geologically, Smøla is separated from the mainland's old Proterozoic gneisses of the Wester Gneiss Region, by the wide fjord and ship's route representing the younger Møre-Trøndelag Fault Zone. Smøla itself show a variety of bedrock geology covering Ordovician ocean crust and gabbroic to granitic intrusions, and larger masses of Devonian conglomerate and sandstone. Smøla's striking landform as a wide flat area in front of the steep mountains represents the strandflat resulting from the Quaternary ice ages. In addition, metallic ore deposits unravel old mining industry, and Viking period - to medieval cultural heritage sites display the use of geological building material.

The geological variety and well-exposed localities have been the basis for integrating Smøla into Geological Survey of Norway's (NGU) database for geological heritage. In addition, the region is covered by both bedrock and superficial deposits maps. Through a collaboration project between the local municipality and NGU, the open information of the geological databases is structured towards different platforms for dissemination of outreach.

Storymap is a digital media integrating maps, images and storytelling. For the Smøla geology, we have produced stories combined with the bedrock map and images of geological localities which take us through the major regional events in the geological timescale. It combines geological processes with telling the good stories as "The volcanic island", "Smøla deep in the crust" and "Stories from the landscape".

The best lesson in geology is learned in field. Smøla is also unique by containing a variety of good localities in a restricted area. In the project we facilitate geology for school education. For the younger pupils we choose the coarse Devonian conglomerates for the exploration of a variety of minerals and rocks. For the older students, an excursion guided by the database of geological heritage combined with information field posters are under development.

The field posters will also facilitate information along existing hiking trails, aimed local hikers, tourists and pilgrim travellers visiting the area. In addition, the region's geological heritage and related stories are integrated in local exhibitions, blogs (ngu.no; blogg.forskning.no/bergtatt) and other outreach publications.

Through all our effort, we aim at contributing to education and raise public awareness for geology and its importance for the society and as intrinsic natural heritage. Our guided geological field trips will contribute to the attraction for tourist, but not least, an enrichment for the daily hiking and nature experience for locals and visitors in the region.

P13.4

Knowledge Centre for Responsible Sourcing of Deep-Sea Minerals in the Arctic Region: A cooperative program between Greenland, the Faroe Islands, Denmark, and Norway

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Our society is highly dependent on raw materials and with the green transition, there follows an increased need for many new metals. Even if recycling is considered a sustainable source of raw materials in the future, we are not yet in a position where there is enough recyclable material to satisfy the production of the batteries needed for the expanding fleet of electric vehicles, permanent magnets for the growing number of wind mill farms etc. The deep sea is a potential future source of many such raw materials.

On one hand, the utilization of marine mineral resources in the Arctic region could potentially be beneficial for several reasons. In Greenland and the Faroe Islands, it could boost the economy and generate jobs. In Norway and Denmark, it could contribute to meeting the ambitions of the Governments of Norway and Denmark to reach their climate goals without being dependent on mineral resources from non-western countries. Eventually, marine minerals could have a positive effect on the security of supply of raw materials for the green transition in Europe, a wish that is well reflected in the new Critical Raw Materials Act and the newly signed MoU between the EU and Greenland. On the other hand, if marine mineral resources are not mined sustainably and responsibly, we risk compromising the extremely delicate ecosystems of the Arctic seas.

To address these issues, a new cooperative network between Greenland, the Faroe Islands, Norway, and Denmark has been formed to discuss some of the pressing issues involved in deep sea mineral activity in the Arctic region. The goal is three-fold: to better understand the resource potential of the deep sea in the North Atlantic and Arctic regions; (2) to better understand the environmental risks and biological communities that will be impacted by any future exploration and exploitation of Arctic natural resources; and (3) to discuss the legal and licensing ramifications of future activities in the region. As part of the project, a high priority includes public outreach and engagement with indigenous communities, including inviting NGO's to participate in the workshops.

P13.5

From Research to Regional Impact: Advancing the Mineral Industry through Geoscience Dialogue

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Geology, the mineral industry, and related environmental research are not necessarily familiar themes to the general public, yet they play a crucial role in shaping the operational conditions, social acceptance, public image, and even funding opportunities of the sector.

The Geological Survey of Finland (GTK) coordinates a collaborative project aimed at improving the development potential of the mineral industry through enhanced cooperation and dissemination of research-based knowledge. The JTF-funded project “Development of the Extractive Industry in Lapland, Northern Ostrobothnia, Kainuu and Central Ostrobothnia” (KAKE) is implemented in partnership with the University of Oulu, Kajaani University of Applied Sciences and the Federation of Education in Central Ostrobothnia.

Knowledge sharing and development work within the project are carried out through joint workshops involving RDI actors, companies, and decision-makers. These workshops help regional stakeholders understand and utilize opportunities presented by the EU’s Critical Raw Materials Act (CRMA) and Finland’s national mineral strategy. A key component of the project is also the compilation of results from numerous Horizon Europe projects in the field, making them accessible and usable for regional businesses even after the project concludes.

In the international context, a major achievement of the project was the organization of the OECD Mining Regions and Cities Conference in collaboration with the OECD and the Regional Council of Lapland in June 2025 in Rovaniemi. The conference attracted participants from around the world, and its main theme focused on improving community participation, trust, and communication in mining.

Both nationally and internationally, the project has promoted knowledge exchange by organizing sessions and delivering presentations at numerous conferences and seminars. The most notable among these are the EU Raw Materials Week (RMW) and the European Geosciences Union General Assembly (EGU).

Overall, the project demonstrates that through collaborative efforts and effective communication, it is possible to foster cooperation between stakeholders and regions that might otherwise remain disconnected.

P13.6

Embedding ESG and human rights principles into geological projects: Insights from Nepal and Zambia

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The Geological Survey of Finland is leading new international projects in Nepal and Zambia that alongside other objectives examine how environmental, social, and governance principles can be embedded into geological and natural resource related work. The role of geoscience in supporting sustainable outcomes is increasingly assessed through ESG frameworks, yet practical approaches to implementation remain limited, and the academic literature in this area is scarce. This poster presents early stage findings from GTK's projects in different regions, which integrate a human rights-based approach within ESG considerations to address community participation, gender and social inclusion, and environmental assessments, alongside technical aspects. Examples of engagement with local actors, accountability and transparency are highlighted, illustrating both challenges and opportunities in different project settings and various regional and cultural contexts. A key lesson is that embedding ESG considerations at the early stages of project design is resource-intensive, but can at best improve both social and environmental outcomes and also strengthen resilience and legitimacy in the long-term. Practical reflections are offered for practitioners seeking to align geoscience projects with international sustainability and responsible business standards.

O14.1

3D printing in the geosciences

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3D printing, or additive manufacturing, encompasses a range of methods of material deposition that can be used from prototyping through research to customisation and mass production of objects. While materials used are mainly polymers/metals, a growing range of rocks, minerals and other geomaterials can be 3D printed. Here, I review how 3D printers can be used in research laboratories from engineering, education, outreach and research perspectives.

A literature review of mineral-based materials shows over 100 different minerals have been used for 3D printing – approximately 2% of ~6000 named mineral species. Of these, 25% have been 3D printed in pure form, 81% as a mix/composite/alloy, and 28% as reaction product. Other geomaterials are used for 3D printing at a range of scales, from precision ceramics to bulk building construction.

In the lab, 3D printers can be used for engineering purposes including part replacement, modification and custom design for e.g. analytical machines, surveying equipment etc. Commonly printed parts include adapters and especially sample holders, allowing optimisation of sample number/shape to analytical machine workspace, leading to increased efficiency/throughput. Standard and engineering grade polymers are common, metals less so. Entry level machines are inexpensive, and initial costs can be covered by efficiency savings in the first few printed objects.

In education and outreach, opportunities arise from the ability to translate digital data of real-world objects and phenomena at different scales, from enlargement of microfossils to scale reduction of large geological features and even entire extraterrestrial bodies (Kyriakopoulos et al. 2021).

In geoscientific research, using inexpensive 3D printers combined with a compounding machine, new geomaterials can be 3D printed, including production of artificial rocks for e.g. petrophysics, rock physics, seismic and rock mechanics experiments (Kong et al. 2021; Zhao et al. 2025); studies in the areas of critical materials traceability; and the production of new materials using geological waste such as mine tailings (circular economy) or inspired by geology (geo-inspiration - Butcher & Corfe 2021).

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O14.2

Finstrati – an online interface to the geological unit database of Finland

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Finstrati is the geological bedrock unit database of Finland (digital lexicon), which is linked to the bedrock map database of Geological Survey of Finland (GTK). The original Finstrati application and database was developed alongside the seamless bedrock map between 2007 and 2010 (Vuollo et al. 2011). The new Finstrati includes web browser-based user interface (finstrati.gtk.fi) and improved database structure.

Unit classification system in the Finstrati is based on the guide “Guidelines and Procedures for Naming Bedrock Units in Finland” (Kohonen et al. 2024). Attribute content of the interface varies depending on the geological unit and includes obligatory fields. Users can navigate in the interface through a hierarchical tree structure where related units are displayed. Key references for each unit are shown on the interface.

Lithostratigraphic and lithodemic units are based on material content. Fundamental units for the lithostratigraphic and the lithodemic categories are formation and lithodeme, respectively. Higher-rank units (suites, supersuites, groups, supergroups, and complexes) are composed of the fundamental units. All units have general description as obligatory field. Fundamental units have type location with coordinates as obligatory fields and additional fields for lithologies, geological contacts, genesis, defined age and correlation. The higher-rank units have limited attribute content, as many properties are already defined in the fundamental units.

Lithotectonic units are divided into crustal, tectonic, and structural provinces (Kohonen et al. 2021). Crustal provinces contain information about igneous crystallization age range. Tectonic provinces are defined by their collisional boundaries. Structural provinces are linked to a tectonic event and show distinct structural characteristics. Tectonostratigraphic units are divided into nappe system, nappe complex, nappe, and thrust sheet, or informal thrust-bounded units: allochthon, thrust stack, thrust block, and thrust sheet. Tectonostratigraphic units contain information of the sole thrust of the unit.

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O14.3

Microearthquake fault plane solutions (FPS) and monitoring crustal stability by interpreting the FPS in terms of complete stress tensors

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The body wave impulse method from 1981 gives well determined FPS for microearthquakes recorded local or regional seismic networks (only one first motion polarity needed). Each 3C-station gives three observations (P, SV, and SH) while only four parameters affecting the impulses are needed (strike, dip, rake, and seismic moment M_0). Already two observing stations give overdetermined equations. In a well known old paper it was argued that the FPS puts only weak constraints on the stress tensor causing the slip. However, that was based on the assumption that the slipping fracture was the only fracture within the earthquake volume which is contradicted by all rock studies. Rock stress measurements have shown that the deviatoric rock stresses are as large as a fractured rock mass can take. This means that the Coulomb Failure Criterion for homogeneous media is a reasonable and realistic approach which puts three constraints on the stress tensor compared to the single constraint by Bott's Criterion. The vertical stress can be assumed to equal the overburden and the CFS for the earthquake slip can be assumed to equal zero. The water pressure p can be assumed to equal the smallest possible principal stress within the water cell containing the microearthquake (p is needed in the $CFS=0$ constraint) which relates it to the vertical stress at the top of the cell. A sixth constraint is given by assuming that nature is not using overkill - it is assumed that the deviatoric deformation energy is smallest possible. These six constraints allow the complete stress tensor causing the slip to be estimated for each microearthquake. The last constraint always favours the steeper dipping plane of the FPS which may be interpreted as explaining why most faults are rather close to vertical. The method has been tested on several hundred thousands of microearthquakes in Iceland. While the estimate of absolute stress tensor requires the use of median values of several microearthquakes the estimated CFS values will be correct also for single observations (independent of the water pressure). This may explain the very good results when monitoring crustal stability (CFS). I will show the stress observations before the two $M=6.5$ EQs 2000 in southern Iceland plus give illustrating examples for $M=4$ EQs in the Hengill area. Several presentations and textfiles (PDF) are freely available from ragnar.slunga@quakelook.se.

O14.4

THERMOCAL – De-risking geothermal development along the Caledonian orogenic belt

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The bilateral THERMOCAL project (THERMOphysical properties of CAledonian rock materials to de-risk geothermal development) addresses a critical stage towards the expansion of geothermal energy with affordable risk in Norway and the UK: reliable, accessible, and quality-assured data on the thermophysical properties of potential source rocks. The project focuses on lithologies associated with the Caledonian orogeny, associated plutons and Precambrian basement, together with thermogeological parameters that are key for the design of both shallow (ground source heat pumps) and deep geothermal systems. THERMOCAL aims to systematically compile, measure, and harmonize data on these key properties across Northern Ireland, Scotland, and Norway by carrying out a dedicated sampling campaign for a new set of empirical data. Thermal conductivity and volumetric heat capacity of rocks will be determined in the laboratory, while internal radiogenic heat production will be derived from laboratory, airborne, down-hole and hand-held field gamma-ray spectrometry. The project will create a unified, open-access database grounded on interlaboratory quality control, ring-testing, and method harmonization, combined with consideration of anisotropy, state of weathering and state of saturation of samples. The new data will also feed into the existing datasets in Norway and the UK. Another component of THERMOCAL is the communication and incorporation of variances and uncertainties in the thermogeological data into geothermal system design. It will ensure data and models are reliable and contribute to informed decisions about system performance and risk.

Compilation of existing thermogeological data in the three participating nations has commenced. Initial evaluation reveals the range of thermal conductivities within the different lithologies and the importance of anisotropy. The first new samples have been analysed, contributing to the re-evaluation of existing laboratory routines and standards.

O14.5

Novel CCUS Technology using Seawater and Ikaite Precipitation followed by controlled CaCO_3 Mineral Alteration for Industrial Usage

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Ikkaton–Climate Solutions offers a novel industrial approach to carbon capture and storage combined with cost-effective utilization of the calcium carbonate minerals produced in the process. It takes advantage of the easily accessible supply of cold seawater ($< 14\text{ }^{\circ}\text{C}$) in coastal areas of the Northern Hemisphere. The industrial process is inspired by the natural formation of the cold-carbonate mineral, ikaite ($\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$) in the marine Ikka Fjord of southwestern Greenland. In Ikka Fjord the ikaite precipitation takes place at the mixing point between Ca-rich seawater and sodic carbonate-rich groundwater of pH 9–11. Ikaite precipitates readily in all calcium carbonate saturated waters when the water temperature is relatively low ($< 10\text{ }^{\circ}\text{C}$), pH is high (> 8.5), and inhibitors of calcite are present. In cold seawater, the Mg^{2+} acts as a calcite inhibitor favouring ikaite when all the above parameters are met. Note, however, that aragonite, a CaCO_3 -polymorf, and monohydrocalcite ($\text{CaCO}_3 \cdot \text{H}_2\text{O}$) can still form as they are not inhibited by $\text{Mg}^{2+}(\text{aq})$. In the Ikkaton process, the mixing sources are two solutions of natural seawater at temperatures $< 14\text{ }^{\circ}\text{C}$, where one is carrying dissolved CO_2 gas. To reach the required alkaline pH, the seawater is subjected to electrolysis, which raises the pH through hydroxide generation and simultaneously shifts the carbonate speciation to favour CO_2 absorption and carbonate ion (CO_3^{2-}) formation. From here onwards the alkaline carbonate-rich seawater is led through membranes stored in a container carrying normal, untreated seawater. The mixing leads to massive precipitation of mm-sized crystals of ikaite on the membranes, which can then be harvested like honey in a beehive by taking the membranes out of the container and scraping off the crystals. When harvested ikaite crystals are dried at room temperature, a mineral alteration into fine-grained calcite takes place. The CaCO_3 solid formed in the Ikkaton process is of very high purity, which makes it suitable for industrial production such as paint, paper, and plastic. All these products use calcium carbonate in their manufacturing where purity is desirable. Hence, the Ikkaton process not only solves the problem of trapping potentially harmful CO_2 gas in stable and environmentally safe minerals, but it also produces an attractive product of pure CaCO_3 of high market value. All sizes of CO_2 emission sources and even mixed gasses can be applied to the Ikkaton process as the plant setup is easily scalable. The only key requirement is access to cold seawater.

O14.6

Long-term carbon accumulation in northern boreal peatlands –the role of the basin bathymetry

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Groundwater dependent nutrient rich sloping fen ecosystem is a typical morphological peatland type for northeastern Finland. To increase the understanding of the carbon dynamics of these ecosystems we investigated the long-term carbon accumulation pattern in sloping fen in the carbonate bedrock area in northern boreal zone.

The study site Puukkosuo is a sloping fen situated in Oulanka in northern boreal zone in NE Finland. Four peat cores were obtained across the study site. All cores were radiocarbon dated for chronological control to calculate the peat accumulation rate. Peat characteristics (peat composition, humification degree, bulk density) and carbon content was analysed to assess the development of the peatland and long-term carbon storage during the Holocene. The peat accumulation rate, based on radiocarbon dates, bulk density and carbon content were used to calculate the long-term carbon accumulation. To assess the role of basin bathymetry to peatland development and to carbon storage, the 3D structure of the Puukkosuo basin was modelled with Leapfrog Geo (Seequent) program based on network of ground penetrating radar (GPR) profiles (5.5 km) across the peatland and reference peat stratigraphy (Åberg et al. 2025).

The records cover the last 9 000 cal yr BP of peatland development and carbon accumulation. The results suggests that the carbon accumulation rate in the basal part of the basin exceeds the average rate in the northern boreal zone, whereas the surface layer demonstrates typical carbon accumulation values. The changes in the carbon accumulation rate are divergent in time between cores, but the major changes follow the basin bathymetry. Therefore, we conclude that here the bathymetry rather than the accumulation period controls the major carbon accumulation patterns. When using point-specific data for calculating regional and/or global carbon storage, it is important to understand the role of basin bathymetry to avoid overestimation of carbon storage.

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O14.7

Natural geological hydrocarbon seepage offshore Northeast Greenland, Arctic Ocean

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Rising concentrations of greenhouse gases cause the Arctic to warm at a faster pace compared to the rest of our planet. This is known as the Arctic amplification and causes an exacerbation of climatic effects such as melting of the ice sheets or warming of the sea water. These changes of environmental conditions may also increase greenhouse gas emissions from natural geologic sources of hydrocarbons including the dissociation of sub-sea floor gas hydrate reservoirs. However, the distribution and contribution of natural geologic methane sources in the Arctic is poorly constrained, especially around Greenland. Here, we present a unique geoscientific data set spanning most of the Northeast Greenland shelf that includes ~120,000 km of 2D reflection seismic data, ~1050 km² of bathymetric and associated water column imaging data from multibeam echosounders, 192 sediment cores including biomarker data and synthetic aperture radar data (Sentinel-1). Seismic data is highly sensitive to fluids in pore space and can thus be used to map entire fluid flow systems. In combination with biomarkers from sediment cores, flares in water column imaging and oil slicks in Sentinel-1 images, the data document extensive hydrocarbon seepage from the sub-seafloor through the water column and to the sea surface. Seepage is primarily focused along permeable beds but also occurs where faults dissect the sedimentary strata or where salt domes reach the seafloor. The seepage is interpreted to be sourced from deep petroleum systems within Northeast Greenland shelf and is likely continuous since the retreat of grounded ice from the shelf. We use an advanced multi-physics gas-hydrate model which shows that the dissociation of gas hydrates beneath the shelf has modulated the flow of fluids and created two distinct pulses (~13ka & 11.2 ka) of methane release since the Last Glacial Maximum. Our new widespread discoveries of seafloor seeps in Northeast Greenland close a significant gap regarding fluid flow in the Arctic, with wide implications for the carbon cycle. The seepage has been favored by the highly erosive ice sheets of the Quaternary cycles, separated by periods of continuous ice retreat from the shelf. The link between glacial retreat and fluid flow is important to understand as it will drive further fluid release from glaciated margins worldwide.

O14.8

Microplastics as indicator of spatiotemporal trends in plastic pollution in sediment cores from the Gulf of Finland, Baltic Sea

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Plastic pollution has occupied the marine environments globally and the Baltic Sea is no exception. In this study a total of 31 sediment layers were analyzed from two sediment cores from coastal and central deep of the Gulf of Finland. The cores were dated and microplastics (MP) were analyzed from the cores to unveil their abundance in different layers of the seafloor sediments. The microplastics were extracted from the sediment samples through heavy liquid separation and basic enzymatic purification protocol treatment and then identified with Fourier transform infrared spectroscopy (FTIR). The microplastics concentrations at the coastal site were considerable higher than at the deep sea. The grain size and loss of ignition analyses support slight changes in the depositional environment in time at both sites. The larger grain sizes correlate with an increase in abundance of microplastics in both sediment cores. The most common plastics types were PE and PP, but abundance of PMMA plastics stands out in both sites. The results of plastic enrichment do not follow linearly the total global production of plastics or increase distinctly over time but rather is fluctuating and affected by international regulation and local improvements in waste water treatment. In addition, watershed processes and climate factors such as ice cover and storm events may affect the discharge, resuspension and sinking properties of microplastics in the marine environment.

O14.9

Evaluating Density-Controlled Sorting in Loess Sediments via Endmember Modelling of Grain-size-shape distributions

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The sediment transport medium, mode, energy, and distance are linked to the grain-size, grain-shape and density of the sedimentary particles. Grain-size analysis has been a well-established technique for almost a century, but within the last few decades grain-shape analysis has also gained a firm footing in inferring sedimentary and transport processes to decipher past climates and environments. One technique to obtain simultaneous size and shape information is Dynamic Image Analysis (DIA). However, both DIA and more traditional grain-size analysis are almost without exception applied to bulk sedimentary samples neglecting the effect of the density.

To assess the role of density, we applied DIA to samples from the Mangshan Loess Plateau, China, which were separated into five density fractions using heavy liquid separation. The resulting dataset was used in endmember modelling of size-shape distributions (EMM-SSD). To evaluate whether sediment sorting occurs based on a combination of size, shape, and density in the examined sample set. Comparing endmembers across density fractions and their stratigraphic distribution allows us to test this hypothesis.

Preliminary results indicate that heavier particles tend to be more elongated or flattened, as median aspect ratios decrease with increasing density. In contrast, grain surface regularity – measured by convexity and Cox circularity – shows no clear relationship with density. These findings suggest that while shape-based sorting is minimal, there may be subtle density-related trends in particle morphology. Further analysis is underway.

P14.1

Stratigraphic framework in Finland – updated classification and guidance

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Stratigraphy encompasses all properties of rock strata, including their lithology, fossil content, correlation and age relationships, and categorises sediment/rock strata into stratigraphic units. Stratigraphy enables interpreting the origin of rocks/sediments and their depositional environments. Stratigraphic work has been carried out for generations and the classification categories have been improved over time. The importance of stratigraphy and classification systems lies in (i) a need to harmonize national and international geological information, (ii) digitalization and establishment of geological databases, and (iii) globalization, i.e. data exchange and interoperability between scientists working in the broad field of geology and geological map data. In Finland, the applicability of the formal bedrock lithostratigraphic approach is restricted for plutonic rocks, but also for gneissic and other highly metamorphic rocks without reliable control of the superposition of the mapped lithological units. The classification of Quaternary deposits in Finland encompasses similar challenges in lithostratigraphy, but for reasons that an establishment of meaningful and mappable glacial and interglacial units is challenging due to their insufficient lateral continuity. Recent developments in geological and geomorphological mapping, new concepts and understanding of rock/sediment and landform classification and advances in geochronological methods have led to a need to review the classification of Finnish bedrock and Quaternary strata. We present recent GTK Bulletin paper called “Stratigraphic framework in Finland – formal classification and practical guidance”, which communicates how modern stratigraphy is best applied in Finland regarding the Precambrian and Quaternary subcommissions of the Stratigraphic Commission of Finland. This publication was compiled to: (i) support consistent geological unit nomenclature, (ii) assist regional geologists and other geoscientists in practical geological work and stratigraphic challenges related to complex, metamorphic bedrock terrains and Quaternary landforms and sediments, and (iii) facilitate the development of the national geological unit database (digital lexicon). This paper offers an updated practical advice on the use of bedrock unit classifications in Finland. It describes how various aspects of regional geology are covered by parallel but distinctly defined unit classifications. The paper also describes ‘Stratigraphic framework for the classification of Quaternary deposits in Finland’. It introduces common practices for the mapping and classification of superficial Quaternary deposits in Finland. It is not a formal guide nor a stratigraphic code, but aims at introducing applicable approaches and practices through which different classifications have been and are currently applied to benefit both scientific interests and more applied research in Quaternary geology.

P14.2

Geological nomenclature in Sweden

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The Swedish Committee for Geological Nomenclature (SCGN) was established in 2019. The members of the SCGN are appointed by the Royal Swedish Academy of Sciences, Class V, on proposal of the Swedish National Committee for Geological Sciences.

The main task of the SCGN is to review and to approve or reject proposals for new and revised, currently informal, names of geological units and other geological features in Sweden. This work is restricted to nomenclature; the SCGN does not take a stance on terminological questions. The SCGN makes decisions on proposed names for geological features, but not geographical features. Geographical and geopolitical names are managed by other authorities. The SCGN addresses name proposals for new geological units and proposals for the formalization of existing ones. All existing names are treated as informal until a proposal for formalization that meets the criteria in the “Guide for geological nomenclature in Sweden” (Kumpulainen 2016) has been approved. The SCGN shall also assist the Swedish National Committee for Geological Sciences in communications regarding nomenclatural issues with international sister organizations, including the International Commission on Stratigraphy.

Formal nomenclature refers not only to lithified stratigraphic units. Unlithified Quaternary units can also be defined formally as lithostratigraphic units. The focus so far in Swedish geology has been on litho-, bio-, and chronostratigraphy. However, in a country dominated by crystalline rock, lithodemic units, geological structures, and large-scale landforms should also be formally defined.

The committee expects that geologists who have in-depth knowledge of a particular unit or structure submit proposals for new units or structures or for the formalization of existing names. The website (<https://www.sgu.se/om-geologi/geologiska-namn-i-sverige/>) provides more information about how to submit a proposal.

New name applications have been taken care of. Two papers, Andersson et al. (2023) and Bengtsson et al. (2024) have been published. A meeting with the Stratigraphic committees of Norway, Finland and Estonia was held in 2024. Work is ongoing to produce a Swedish version of the ICS stratigraphic chart.

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P14.3

New data on epigenetic phosphate mineralization in the Hopukka quartzite quarry, Norrbotten, Sweden

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The Hopukka quartzite quarry is located in the northern Norrbotten ore province, an area that hosts both iron oxide–apatite (IOA, Kiruna-type) and iron oxide–copper–gold (IOCG) deposits. The closest known deposit is the IOA Painirova deposit, situated about 2 km east of Hopukka. The study area is underlain mainly by Orosirian supracrustal rocks (mafic to intermediate volcanic units and quartzite), and Lina suite granite. Moreover, it is positioned in the immediate vicinity of two major regional structures: the Karesuando–Arjeplog Deformation Zone (KADZ) and the Nautanen Deformation Zone (NDZ) (Bauer & Andersson 2023).

The phosphate mineralization described originates from the southern part of an abandoned quartzite quarry. It is associated with resiliified zones in quartzite, which occur in close proximity to quartz/pegmatite/greisen veins. Two principal mineral assemblages can be distinguished. The first is directly linked to the quartz veins and consists mainly of quartz, minor muscovite, two varieties of tourmaline (with compositions intermediate between schörl and dravite), accessory apatite and zircon. The second assemblage reflects the activity of late-stage hydrothermal fluids and resulted in the formation of a younger phosphate association. The most abundant phase is turquoise ($\text{CuAl}_6(\text{PO}_4)_4(\text{OH})_8 \cdot 4\text{H}_2\text{O}$), which occurs as irregular crusts and fracture fillings within the resiliified zones. Concentric wavellite ($\text{Al}_3(\text{PO}_4)_2(\text{OH})_3 \cdot 5\text{H}_2\text{O}$) aggregates, reaching several centimeters across, are also present in fractures. The described phosphate mineralization co-occurs with recrystallized quartz and hematite in fractures. Moreover, the crystallization of monazite and Ti oxides, associated with hematite in quartz veins, results from a late-stage hydrothermal overprint.

In the immediate surroundings, secondary hydrothermal phosphate assemblages have previously been documented in the Leveäniemi pit – IOA deposit (Bjällerud 1989; Nysten et al. 2020). There, distinctive Fe–Ca–Al phosphates occur within “apatite-bearing magnetite ore partly oxidized to hematite” and are found filling vugs together with goethite. In contrast, Hopukka is characterized by widespread Cu phosphates, most notably turquoise - representing the first reported occurrence of this mineral in Sweden. Although the phosphates are spatially associated with silicified zones linked to quartz veins, the possibility of a deeper phosphorus source for the remobilized mineralization cannot be excluded.

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P14.4

Glacial landsystem of Blautukvíslarjökull (central Iceland): a record of multiple surges

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Glacier surges affect all the major ice caps in Iceland. Most outlet glaciers of Hofsjökull, the third largest Icelandic ice cap, are classified as surge-type or reveal some geological evidence of surging. Here, we investigate the geomorphology at Blautukvíslarjökull, which behavior has not been considered as surge-type before due to the lack of historical observations of active surging. Geomorphological mapping reveals characteristic landforms for surging glaciers, including overridden end moraines and crevasse-squeeze ridges (CSRs). The forefield can be divided into the western and central parts with long flutes, widespread CSRs and several overridden end moraines, the eastern part with sparse CSRs and multiple overridden end moraines, and the northern part with fluted terrain and ice-cored moraines, but without CSRs. The youngest end moraine corresponds to glacier extent around 1995, suggesting that the last surge occurred in the 1990s. In total, the surge landsystem of Blautukvíslarjökull reveals at least four surges marked by end moraines.

P14.5

NordSIMS-Vegacenter: analytical developments and novel techniques

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The NordSIMS-Vegacenter national research infrastructure, hosted at the Swedish Museum of Natural History, Stockholm, is an integrated research center for (micro-)analysis and micro-imaging in the earth, environment and planetary sciences. The center is equipped with SIMS, TIMS, MC-ICPMS, and HR-ICPMS instruments, two laser ablation systems, SEMs, and supporting facilities, including mineral preparation and clean-room laboratories. The principle scientific goal of the infrastructure is to advance the knowledge of the natural world via groundbreaking geochemical and isotope analyses on the widest possible range of samples. As dedicated research infrastructure, scientists are welcome to apply for analytical time at our facilities. The research that has been done at the infrastructure over its three decades of operation has scopes ranging from atoms to planets, from the deep Earth to the stratosphere, and from the Hadean to the present. In this contribution, we present a brief overview of our analytical capabilities and some of the more novel methods that NordSIMS-Vegacenter offers.

P14.6

Permian-Triassic terrestrial mudstone of southern Britain: features and application for paleoenvironment reconstruction

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The middle Permian to late Triassic (~260–201 Ma) represents one of the hottest intervals of the past 500 million years, marked by profound environmental changes across the Pangean supercontinent, including the widespread development of dusty deserts and the establishment of a strong monsoonal climate. However, relatively detailed information on climate variability during this hothouse interval remains limited, especially on land. Terrestrial mudstones of this age are found in large areas of northern and western Europe, and offer valuable archives for reconstructing hyper arid terrestrial paleoclimate in this hothouse.

Basin marginal terrestrial mudstones crop out along the southwest coast of England (Aylesbeare and Mercia Mudstone Groups; Hounslow et al. 2016; Hounslow & Gallois 2023), and are likely formed by terrestrial deposition of windblown desert dust, potentially in playa lake settings. These mudstones may serve as an analogue for Quaternary desert loess systems, potentially allowing reconstruction of late Permian–Triassic climate dynamics, and orbital forcing.

To address this and to undertake a detailed and systematic analysis of these we applied mineral magnetic methods to investigate environmental controls on magnetic susceptibility parameters and assess their use as a past climate proxy in the mudstones. Low-frequency (976 Hz) and frequency dependent magnetic susceptibility measurements reveal substantial variation in these sequences, corresponding to stratigraphic alternations between green-grey silty mudstones and red mudstones, which may reflect large-scale fluctuations in water table levels and humidity, driven by orbital parameters. Temperature-dependent magnetic susceptibility experiments indicate that paramagnetic minerals and magnetite are dominant contributors to magnetic signal in all facies, with hematite input in red mudstones. Initial anisotropy of magnetic susceptibility (AMS) measurements suggests that primary depositional magnetic fabrics characterised by vertical-to-bedding $K_{\min}$ directions and mostly oblate ($T > 0$) fabrics are preserved and have potential for wind direction analyses. Overall, we propose that combining these magnetic proxies provides new insights into both dust dynamics and likely monsoon-driven humidity fluctuations during one of Earth's most prolonged arid intervals.

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P14.7

Rock carving depth reflects carvers' geological insight

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Rock art is a remarkable window into Bronze Age societies, offering insights into culture, beliefs, and interactions with their environment. The exceptional well-preserved art in Bohuslän, Sweden, is a prime example and has been recognized as world heritage in 1994. With >2000 different sites it represents the highest density of Bronze Age rock art in Scandinavia. The images are carved into Bohus granite, which appears as a great canvas prepared by erosion and polishing during the last ice age. The hardness of granite prompts questions about how these carvings were achieved using the tools and materials available at the time, and whether all granite surfaces were equally suitable for carving.

Unlike previous studies on the effect of post-glacial surface weathering on carving depths, our research reveals that the last glacial period itself played a crucial role in preparing the granite for carving. Glacial processes created a thicker, weakened surface layer on the granite, which corresponds to the depth of many carvings and likely influenced the selection of rock surfaces. While the entire region was impacted by glacial processes, local variations led to differences in thickness of the weakened layer, often in the millimeter range. This variability suggests that Bronze Age carvers had a solid understanding of the rock's properties, enabling them to identify the most suitable surfaces for their art. This level of expertise positions these ancient artists as precursors to modern geologists, demonstrating a sophisticated relationship with their natural environment.

P14.8

Nickel Isotopes in the Talvivaara Black Shale Ni Deposit, Finland: Possible Biological Effects on Ni Signatures

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The Talvivaara Ni–Zn–Cu–Co deposit in eastern Finland represents one of the largest Paleoproterozoic black shale–hosted metal resources, formed in a redox-stratified rift basin between 2.1 and 1.9 Ga. We present new nickel isotope ($\delta^{60}\text{Ni}$) data from drill core samples spanning 82–273 m depth. Values range from -0.43 to $+0.71\text{‰}$, overlapping with mafic/ultramafic weathering products and hydrothermal fluids, but lighter than seawater, riverine input, and Fe–Mn crusts. Nickel is primarily hosted in Fe-sulfides (pyrrhotite, pyrite and pentlandite), with strong negative correlations between $\delta^{60}\text{Ni}$, S, and total carbon, indicating preferential incorporation of isotopically light Ni during sulfidization and organic matter interaction. The lightest values (-0.43 to -0.03‰), however, occur between 119–152 m and coincide with elevated Fe/Mn ratios, positive Eu anomalies, $\Delta^{33}\text{S}$ anomalies, and authigenic Ni enrichments, consistent with near-field hydrothermal input and microbial sulfate reduction at redox boundaries. By contrast, heavier $\delta^{60}\text{Ni}$ values are associated with more oxic intervals where Ni resides in pyrite and Fe/Mn oxides. These results suggest that the Talvivaara $\delta^{60}\text{Ni}$ signature reflects a combined influence of mafic/ultramafic source rocks, hydrothermal fluids, and diagenetic sulfidization. Our findings demonstrate that nickel isotopes may be effective tracers of metal cycling in ancient organic-rich basins, resolving the interplay between provenance, fluid influence, and early diagenetic redox processes in black shale–hosted Ni deposits.

O15.1

A Continuum-Based, DFN-Consistent Numerical Approach for Modelling Hydrogeochemical Evolution at Olkiluoto, Supported by a Multitude of Geological Indicators (OL-STAR)

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Demonstrating the long-term safety of deep geological repositories for spent nuclear fuel (SNF) requires ensuring stable hydrogeochemical conditions in the host rock over timescales of hundreds of thousands of years. At the Olkiluoto site (Finland), a key concern is the evolution of dissolved sulfide in groundwater due to its potential to corrode copper under anoxic conditions. Although sulfide is detected only at low levels, elevated concentrations could compromise SNF disposal long-term safety. Sulfide production and attenuation are governed by hydrogen, sulfate, iron availability and microbial activity, all tightly coupled to site hydrodynamics, making modelling highly challenging.

The [OL-STAR](#) project represents a unique advances to embrace complex reactive transport modelling at site scale. A comprehensive understanding of site-specific processes, developed through extensive field investigations, is now incorporated into palaeo-hydrogeological modelling that accounts for external drivers such as shoreline evolution induced by land uplift, and compared against present-day field data. Reactive transport in Olkiluoto's fractured crystalline rocks exhibits strong coupling between hydrological and hydrogeochemical processes (e.g., matrix diffusion, sulfur cycling), resulting in a highly non-linear model, necessitating efficient numerical frameworks. An advanced continuum-based approach for the high-performance computing (HPC) of reactive transport in fractured media was developed in PFLOTTRAN (Lichtner et al. 2015), incorporating density-driven flow, electromigration, and physical and geochemical heterogeneity. The model parameterization, covering flow, transport, and geochemistry (hydraulic conductivity, kinematic porosity, surface area and abundance of minerals), is consistent with the underlying geological structural conceptualisation and unparalleled field data from Olkiluoto. A cation exchange method, equivalent to the Nernst-Planck electromigration equations (Trinchero et al. 2022), is introduced as a practical approach to simulate anion exclusion within the reactive transport framework.

The holistic hydrogeochemical reactive transport modelling methodology is demonstrated through simulations of Olkiluoto's palaeo-hydrogeochemical evolution using the LUMI supercomputer (Kajaani), with the ultimate goal of predicting long-term groundwater chemistry to support the SNF disposal safety case over the next glaciation.

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O15.2

Rethinking the redox ladder: Production of dark oxygen in bedrock groundwater

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Molecular oxygen (O₂) produced by photosynthesis at the Earth's surface is released into the atmosphere and dissolves into groundwater but, as an effective electron acceptor, is readily consumed along the flow path. For example, underground nuclear waste repositories are estimated to become anoxic within 200 years (King et al. 2010). Although O₂ is often detected in deep groundwater samples, it has typically been attributed to air contamination. Yet, O₂ can form in the dark subsurface via non-photosynthetic processes, including microbiological activity (Ruff et al. 2023) and abiotic water-rock reactions (e.g., Ershov & Gordeev 2008).

We isolated a fracture zone at 128 m depth in Kopparnäs, Inkoo, Finland, using packers and pumped for several days to collect samples for dissolved and free gases and microbiology to explore the presence of O₂ and related metabolisms. Groundwater samples contained 3.37–3.69 mg L⁻¹ dissolved O₂. Small amounts of O₂ (~1 vol-%) were also detected in the free gas phase and continuously observed via online monitoring of the pumped water. Dissolved gases and their isotopic ratios differed clearly from an intentionally air-contaminated sample. Photosynthetic O₂ partially consumed along the flow path could also be ruled out. Instead, δ¹⁸O(O₂) values of 19.05–21.86 ‰ VSMOW are consistent with in-situ O₂ production via biotic or abiotic reactions, such as dismutation or radiolysis of water, or molecular diffusion.

Although molecular diffusion of atmospheric O₂ can yield a trajectory similar to in-situ production in Δ¹⁷O vs. δ¹⁸O space, several lines of evidence support the presence of oxic niches in Kopparnäs. Substantial helium (up to 2.65 vol-%) indicates long groundwater residence time and high potential for radiolytic O₂ formation within the studied fracture zone. In addition, the microbial community at this depth contained genes for protection against oxygen radicals and metabolic pathways that depend on O₂.

The presence and continuous supply of O₂ in deep groundwater environments can profoundly influence the long-term safety of nuclear waste disposal, as corrosion reactions, microbial activity, mobility of uranium and other redox sensitive elements are strongly affected by O₂ availability.

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O15.3

Fracture-filling smectites as analogues for engineered barrier system bentonites – new results from the Olkiluoto repository

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Bentonite is used as a sealant in many repository designs for radioactive waste disposal, including ONKALO that is approaching its operational status at Olkiluoto, Finland. While bentonite stability has been extensively studied in laboratories and via modelling, less emphasis has been placed on assessing the overall long-term stability of natural smectites found in Finnish bedrock. These natural occurrences offer valuable insights for safety evaluations. Smectite minerals are known to occur as fracture-filling clays at Olkiluoto and elsewhere (see e.g., Reijonen 2024).

Currently, Posiva is assessing the bedrock mass at repository level (at around – 430m depth) via pilot holes and in the first tunnels excavated for the repository. From these samples, fracture and fault zones have been identified with fracture-fill minerals. This study presents initial results from the samples collected at the repository depth. Materials, including fault gouge and fracture fillings, were analysed using Short Wave Infrared (SWIR) spectroscopy (n=167), X-ray diffraction (XRD, n=10), scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS, n=6), and electron probe microanalysis (EPMA, n=4).

SWIR analysis identified montmorillonite spectral features in several samples. XRD confirmed the presence of smectite and mixed-layer clays in varying quantities. SEM-EDS and EPMA provided mineralogical and chemical data, although the detection of smectite was limited by sample preparation challenges. Three clay mineral assemblage types were identified from the XRD dataset, with mixed-layer clays being most common and pure smectite rare.

The mineral composition of fracture fillings shows similarities to the bentonite that is used in engineered barriers, supporting the use of natural analogues in the safety assessments. However, expanding the sample set, improving in situ analysis, and exploring dating methods for smectite phases are recommended. While the identification of smectite types can be challenging, the results indicate the presence of montmorillonite (Na-type identified in one sample), whereas other smectites were not detected. Vermiculite was observed in some samples. These findings contribute to the understanding of bentonite long-term stability of bentonite and fracture-filling clays in crystalline bedrock environments. They also suggest that natural montmorillonite occurs at repository depth, albeit in very small quantities.

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O15.4

The Mörtsjö Fault System: A glacially induced fault that produced significant seismicity in the late Holocene

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An understanding of past and present seismicity is a prerequisite for the siting and design of long-term storage facilities for nuclear waste. In Fennoscandia, discussions of seismicity often revolve around glacially induced faults. It has long been known that these structures ruptured to the surface during or shortly after deglaciation accompanied by high-magnitude seismicity (>M7) (Lagerbäck & Sundh 2008). Additionally, these same structures host most of the modern micro-seismicity in Fennoscandia (Lund et al. 2021). Recent studies, however, document paleo-seismicity that does not belong to either of these categories. Specifically, two studies suggest fault displacement accompanied by significant magnitude seismicity (> M6) along multiple glacially induced faults during the late Holocene (Ojala et al. 2019, 2018; Olesen et al. 2021).

The current study (Smith et al. in press) adds to this growing body of evidence of significant magnitude seismicity during the late Holocene. The Mörtsjö fault system in Hälsingland, central Sweden was first recognized as a series of scarps crosscutting glacial sediments and landforms in LiDAR imagery. Stratigraphy and radiocarbon dates from three trenches excavated across the scarps indicate two fault ruptures shortly after deglaciation and a third fault rupture about 3200 years before present.

The two deglacial age fault ruptures are also documented in hydroacoustical surveys of nearby lakes. The hydroacoustical data reveal numerous landslides in glacial sediments as well as the fault itself.

Collectively, these data indicate that the Mörtsjö fault is a glacially induced fault that hosted a M 5.0-5.5 earthquake during the late Holocene.

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O15.5

GIS assisted site screening and site selection

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Effective site screening is a foundational step in nuclear waste management, ensuring long-term safety, minimizing environmental risks, and fostering societal acceptance (IAEA 2015). Nuclear waste must be securely isolated from the biosphere for durations ranging from several centuries to over a million years, depending on the waste type. By narrowing down suitable regions early in the process, subsequent investigations can be focused more efficiently, reducing both time and costs.

A semi-automated GIS-methodology was developed at Geological Survey of Finland for site screening and selection, particularly for the long-term storage of hazardous materials such as radionuclides. The methodology integrates both exclusionary and discretionary criteria to identify and rank potential storage sites. Exclusionary criteria—such as proximity to seismic zones, population centers, and nature conservation areas—are used to systematically eliminate unsuitable regions. Discretionary criteria, including soil type, proximity to infrastructure, are then applied to score the remaining areas and rank potential sites.

The workflow involves lineament interpretation from aerogeophysical maps, LiDAR, and bathymetric maps, applying scores and weighting factors to a grid, delineating optimal sites and ranking them. The top-ranked sites are further evaluated through field visits and the most optimal ones are reported and recommended for further site studies.

The approach is adaptable to different storage needs and utilizes tools like ArcGIS Pro and Model Builder for efficient, repeatable and easily iterated analysis. The model also serves as documentation of the process, including parameters and scoring. This adaptable methodology balances safety, environmental integrity, societal factors, and economic feasibility, offering a robust framework for responsible site selection.

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O15.6

MICA II: Natural Copper Analogues from the Keweenaw Peninsula for Repository Safety

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Research on the corrosion of native copper, together with its geological history, informs predictions of copper stability in repository systems. Copper is a key material in several disposal concepts, including KBS-3 in Sweden and Finland (SKB 2022). Natural and archaeological analogues complement laboratory studies and provide insights into copper corrosion processes relevant to safety cases (Miller et al. 2000).

The native copper deposits of the Keweenaw Peninsula, Michigan, occur in subaerial basaltic lava flows and minor sediments of the c. 1.1 Ga Midcontinent Rift. Hydrothermal fluids precipitated copper and associated minerals between 1.07 and 1.04 Ga (Bornhorst & Lankton 2009). Following Precambrian erosion and Paleozoic burial, Quaternary glaciations ultimately re-exposed the copper deposits at the surface. The district, mined from 1845 to 1968, remains the world's largest concentration of native copper.

The Michigan International Copper Analogue (MICA I) Project assessed copper stability and proposed a classification of analogue types (Aaltonen et al. 2023).

The ongoing MICA II targets three analogue types for repository applications:

1. *Bedrock copper* for baseline data on stability during geological evolution;
2. *Copper-in-clay* as a potential close analogue to repository conditions;
3. *Copper sulfides* to extend understanding to sulfur-bearing environments.

The aim is to build a coherent dataset supporting repository safety cases and stakeholder communication on long-term evolution and possible perturbations.

MICA II fieldwork in May 2025 yielded 61 samples from six mines, waste piles, and the A.E. Seaman Mineral Museum, Houghton. Structural data were collected to document geological context. Planned analyses include X-ray tomography, petrophysical tests, XRD for clay minerals, SEM mapping, FE-EPMA for compositions, and K/Ar dating of fault clays.

MICA II Project is a collaboration between the Swedish Nuclear Fuel and Waste Management Co, the Korea Atomic Energy Research Institute, and the Geological Survey of Finland.

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P15.1

Thermodynamic evaluation of oxygen-dependent biogeochemical pathways in deep bedrock groundwater: Insights from Olkiluoto and Kopparnäs

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Understanding deep groundwater dynamics is crucial for assessing the long-term safety of nuclear waste disposal. This need has been emphasised with the recent finding of in-situ oxygen production in deep aquifers (Ruff et al. 2023), including Finnish deep bedrock groundwater (Kuusiluoma 2025), which challenge the assumption that repositories evolve towards absolute anoxicity after the initial oxic phase. Anoxic conditions limit redox-sensitive radionuclide mobility, microbial activity, and canister corrosion, which will be increased in oxic conditions. Therefore, ensuring long-term redox stability is crucial to nuclear waste repository safety.

Our study aims to provide overview of biogeochemical cycles that may be critical for the long-term safety, focusing on oxygen production and consumption under repository conditions and their impact on redox-sensitive elements. We used in-situ concentrations of redox sensitive species including major ions and trace elements in groundwater and gas from the Olkiluoto repository site (418-449m depth), and an analogue site in Kopparnäs (125-175m depth), southern Finland. Microbial oxygen-dependent metabolic pathways were evaluated using Gibbs free energies and related energy densities. In total, 56 reactions were considered, involving major nutrients (C, N, S) and trace elements (Fe, Mn, U), depending on the site-specific data availability. Sixteen reactions involved oxygen as a direct electron acceptor.

The results reveal that in Kopparnäs, sulfide oxidation coupled with oxygen is thermodynamically favourable and associated with the highest energy density, illustrating the dominant role for oxygen consumption. In Olkiluoto, assuming dissolved oxygen exists, e.g., in microoxic niches, aerobic methane oxidation appears most favourable both thermodynamically and energetically. However, ONK-KR16 borehole shows sulfide oxidation as highly favourable reaction with medium energy density, whereas the deeper ONK-PVA14 exhibits higher energy density for aerobic methane oxidation, suggesting spatial variability in dominant redox processes and available metabolic energy.

The findings can provide insights into oxygen-driven microbial metabolisms in Finnish deep bedrock groundwater and enhance understanding of oxic-anoxic conditions in terms of energy availability and biogeochemical cycles including cryptic cycles of elements relevant to long-term repository safety, particularly regarding the impacts of microbial activity and redox dynamics.

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P15.2

Influence of environment and microbes on corrosion behavior of welded steels in the LILW repositories (MICWEST-project)

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MICWEST project (SAFER2028) investigates the interactions between environment, microbes and welded steel materials within the context of Finnish nuclear waste management. In Finland, low and intermediate level nuclear waste (LILW) will be disposed in underground repositories, where welded steel and concrete structures are used for waste containment and isolating waste from the environment. During repository evolution, these containers will be exposed to unique geochemical and microbiological conditions, e.g. via groundwater contact. Understanding the potential for microbially influenced corrosion (MIC) in these settings is important for ensuring the long-term safety and integrity of waste containers in the LILW repositories.

MICWEST consists of multiple work packages, focused on short-term studies on corrosion, electrochemistry and microbial community activities during different phases of repository evolution, and long-term test set-ups to verify weld durability.

MICWEST long-term studies follow the development of planktic and weld surface biofilm microbiomes and evaluates their effect on corrosion processes in an anaerobic laboratory set-up mimicking the LILW repository conditions. Two laboratory set-ups were established. First contained natural groundwater from the Hästholmen, Loviisa, with local microbiome, and second set-up was established in simulated groundwaters inoculated with enriched MIC related microbial groups like sulfate reducing bacteria (SRB) originating from the Hästholmen groundwaters. Steel types included pressure vessel steel as used in Finnish nuclear power plants, EN 1.0038 carbon steel and stainless steels EN 1.4404 and EN 1.4541. Welding types were gas-metal-arc welds and sub-merged arch welds, established between mixed or single materials as expected to occur in waste containers. Post-weld cleaning methods will be evaluated such as grinding/brushing and pickling. Study includes 2 samplings, first 4-month incubation finalized, and 3-year sampling will be done in 2027.

MIC estimations rely on multiple lines of evidence to establish understanding whether the onset and progress of corrosion could be influenced due to biological factors. Here we planned a multidisciplinary approach merging microbiological and material scientific methodology to understand the nature of corrosion phenomena. Using dPCR, epifluorescence microscopy (DAPI), and metabarcoding of bacteria, archaea, fungi, and SRB we aim to enumerate different microbial groups and reveal established microbial community structures. Steel and weld samples analyses include material characterization via scanning electron microscopy combined with energy-dispersive X-ray spectroscopy (SEM/EDS), electrochemical measurements (OCP, LPR, EIS, galvanic corrosion), and gravimetric mass loss measurements to estimate proceeding of corrosion in steels, welded joints and heat-affected zones. SEM will also be used to visualize the biofilm structures formed over weld and steel surfaces.

P15.3

Preliminary studies on geological aspects of managing high-level nuclear waste in Norway

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After 70 years of activity, the research reactors in Halden and Kjeller have been taken out of operation. Norwegian Nuclear Decommissioning (NND) is responsible for decommissioning the Norwegian research reactors and managing ultimate disposal of the nuclear waste. As a fraction of the total volume of waste that needs handling, approximately 17 tons of high-level radioactive waste has been produced from the reactors and must be handled and disposed of underground in a safe manner.

Since 2020, NND has involved the Geological Survey of Norway (NGU) in preliminary geological studies for future site investigations. The work carried out in Sweden and Finland, as well as reports prepared by the Finnish AINS Group on behalf of NND, have been an important basis for the studies conducted by NGU.

First, NGU conducted a national study to compile data of various geological aspects relevant to a site selection process for a radioactive waste repository in crystalline bedrock. A wide range of geological disciplines were included in this work, including bedrock geology, Quaternary geology, geohazards and geological resources (e.g., metals, industrial minerals, construction aggregates, and groundwater). The study was based entirely on existing datasets and maps. The compiled maps were used to give an overview of the regional variations in terms of geological aspects relevant for a future site selection process in Norway.

As a continuation of the national study, a more detailed study was conducted in the municipalities of Halden and Aremark, located in south-eastern Norway near the research reactor in Halden. The municipalities were selected for this study upon request from NND and upon the results from the national study. The detailed study served as a basis for gathering new geological data, improving the geological knowledge within the two municipalities and establishing a list of geological criteria that can be used in a future site selection process. A selection of geological criterion was assessed in this study: structural geology, mineral resources, sediment thickness, glacial erosion and seismicity. The assessments were based on existing geological maps and data, as well as new data from preliminary field investigations of surface bedrock and Quaternary geology. The outcomes were compiled into maps indicating geological complexity. Greater complexity indicates a higher risk of geological unsuitability for hosting a waste repository and/or limited geological knowledge.

Results, methodology and lessons learned from these studies will be valuable in the geological aspects of a future site selection process for a radioactive waste repository in Norway.

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O16.1 (Keynote)

Orogenic gold deposits in evolving orogens: a global perspective with examples from Paleoproterozoic Finland and Greenland

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Orogenic gold deposits are a major gold resource with approximately 40% of the global supply originating from them. Europe's largest orogenic gold deposit, Suurikuusikko (~64 Mt), is situated in Finland. Moreover, recently developed orogenic gold deposits with atypical metal association (Co, Cu, Ni, Sb, U, and REE) show the potential for critical mineral byproducts in particular in Finland.

Orogenic gold deposits formed in orogens through geological time and are controlled by major faults or shear zones. They represent an epigenetic hydrothermal ore deposit type, where gold is hosted in quartz $\pm$ carbonate veins with narrow hydrothermal alteration halos. The hydrothermal alteration assemblages vary with PT conditions (200-700°C, 1-7 kbar). The paragenesis and absolute timing indicate that orogenic gold deposits form late in the orogenic evolution of orogens. However, common genetic models suggest formation in fore arc- or back arc settings.

Recent investigations show that orogenic gold deposits commonly formed during several hydrothermal stages during retrograde terrane exhumation. Hydrothermal gold mineralization is often tens of million years younger than their host rocks. It generally post- or predates granite intrusions significantly. This suggests that fore arc- or back arc setting may be restricted to those deposits in the North American Cordillera, where they formed at the same time as the Cu-porphyry deposits. Most orogenic gold deposits form after collision or accretion along major shear zones with inverted metamorphic gradients or in a metamorphic core complex setting.

The ca. 1780-1760 Ma Nalunaq and Vagar Ridge deposits in South Greenland formed during retrograde terrane exhumation in a regional-scale frontal and lateral ramp structure. They are hosted in juvenile rocks, but granitic magmatism either pre- or postdates gold mineralization. Stable isotopes indicate a metamorphic fluid source.

Similarly, Finnish orogenic gold deposits show evidence for a metamorphic fluid source. Wall rocks in the Paleoproterozoic belts show depletion in gold and other elements with increasing metamorphic grade, indicating metal mobilization during metamorphic devolatilization. Lithological variability and related variability in metal liberation may explain different metal endowment in the orogenic gold deposits with atypical metal association. In the Pohjanmaa Belt, the orogenic gold deposits formed in two stages during regional deformation and retrograde metamorphism at ca. 1880-1820 Ma and ca. 1810-1800 Ma. This marks the Svecobaltic Orogeny. The Finnish orogenic gold deposits of the Pohjanmaa Belt thus are a good example for mineralization late in the orogenic evolution of the host terrane, where active subduction or terrane accretion is located several hundred kilometres away. Such a complex tectonometamorphic and hydrothermal evolution is now more and more recognized globally and appears to be a characteristic feature of orogenic gold deposits.

O16.2

Pyrite Geochemistry of the Heinä Central Au (Cu-Co) Deposit, Finland

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Many Finnish gold deposits are commonly referred to as 'atypical' as they are often enriched in copper and cobalt. Heinä Central, located in the Central Lapland Belt, Finland, is one such 'atypical' deposit and is the Au(Cu-Co) satellite of the Ikkari-Au deposit, set to be one of Europe's largest gold mines. Understanding the deportment of base metals within these gold deposits will optimise metal recovery, while increasing the European security of supply for these metals.

In this study, in-situ pyrite trace element data and S-isotopes are used to understand the evolution of mineralisation at Heinä Central. Textural and trace element characteristics of pyrite indicate five distinct generations of pyrite:

Group 1 pyrite are cobalt and arsenic enriched and are associated with intermediate copper mineralization with subeconomic gold. Group 2 pyrite is cobalt and nickel enriched located in cobalt-only mineralised zones (i.e., not mineralised in gold or copper). They are subhedral, massive and pitted in appearance. Group 3 pyrite have moderate, equal enrichment of cobalt and nickel and are texturally similar to Group 2 pyrite, containing elevated gold in the pyrite lattice. They are either located in massive pyrite intervals or are closely associated with pyrrhotite in high copper mineralisation zones but do not appear to be associated with economic gold intervals. Group 4 pyrite is associated with anhedral aggregates of pyrite with visible gold and patches of pyrrhotite in high grade gold intervals. Group 5 pyrite is low in trace elements and is interpreted as metamorphic in origin. They are associated with carbonate veins and carbonate groundmass, and are common across both subeconomic and economic intervals.

S isotope values vary between +6 and +18 ‰. Preliminary interpretation suggests two end member fluids; 1) a possible basinal brine with heavy sulphur and 2) a second fluid with lighter sulphur originating from either magmatic fluids, or with sulphur leached from igneous rocks. One sample containing visible gold contains heavy S, while samples with high cobalt and copper have variable S isotopic values, and may reflect mixing or gradual reduction of an oxidized fluid.

The pyrite-pyrrhotite-chalcopyrite mineralogy and range of sulphur isotopes combined with the volcano-sedimentary geological setting, suggests that Heinä Central mineralisation may be related to the formation of VMS deposits with subsequent overprinting of orogenic gold, as seen in many orogenic gold provinces globally (e.g. Yilgarn Craton, Australia). This is supported by the varied pyrite geochemistry at Heinä Central which reflects hydrothermal overprinting of different mineralising systems as seen in other 'atypical' Finnish deposits, like the Rajapalot Au-Co deposit.

O16.3

Primary ultra-high-grade Au in mid-crustal veins: fracture morphology, microtextures and viscoelastic fracture growth

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The classic low to moderate-grade (1 - 25 ppm) style of orogenic Au mineralisation is composed of fine-grained disseminations of free or sulfide-bound Au localised within altered host rocks or laminated composite veins. However, many Au deposits also contain localised lodes or discrete veins with significant ultra-high-grade Au enrichment (UHG-Au, 1000's to 10 000's ppm). UHG-Au mineralisation style is typically vein-hosted, and its coarse nuggety character is texturally distinct from the classic mineralisation style. The extreme Au enrichment seems to exceed the solubility limits of Au in typical ore-forming fluids, making it difficult for current mineral systems models to account for these UHG-Au occurrences. The genesis and depositional environment of UHG-Au were investigated at the Beta-Hunt Au mine, Kambalda, Western Australia. The Beta-Hunt is a mid-crustal orogenic Au deposit that hosts both classic disseminated Au and coarse vein-hosted UHG-Au. We employed a multi-disciplinary methodology, conducting vein morphological characterisation, microtextural analysis, 2D μ -XRF mapping and 3D X-ray tomography. Our observations show that gangue and coarse Au precipitated within fluid-filled open space. Therefore, the UHG-Au formed within progressively dilating fractures during a single or relatively few opening-infill cycles. Our meso- to microscale textural observations deviate from the expectations of classic mineral system models, which usually assume that the growth of hydrofractures is associated with rapid, quasi-instantaneous brittle fracturing. Growth of such fractures is described by the time-independent linear elastic fracture mechanism (LEFM). We compare our results with predictions of LEFM and, instead, contextualise our observations following time-dependent theory of viscoelastic fracture growth. Based on the viscoelastic theory, we propose a model for the development of UHG-Au vein morphology and infill mineral textures relevant for vein networks hosted by brittle-ductile shear zones. The model produced in this study couples the generation of growth space for coarse Au nuggets while enabling sustained fluid flow capable of steady nutrient supply. Our results highlight how sustained open fractures may have a large impact on hydraulic conductivity of shear zones, especially in mid- to lower crustal environments where the existence of viscoelastic fracture networks may partially explain the apparently uneven distribution of major fluid pathways.

O16.4

What controls on high grade gold mineralization?

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Over the past five decades, global demand for gold has tripled, yet the industry is confronted with a shrinking supply base as ore grades continue to fall, deposit discoveries decline, and exploration increasingly targets deeper levels of the Earth's crust. Lower grades require greater energy and material inputs for extraction, which in turn increases waste production along with environmental and social costs. High-grade ore bodies are therefore critical to project viability, as they deliver rapid, high-margin returns that can offset capital and operating expenditures while enabling the development of larger, lower-grade resources. At present, near-mine exploration for ultra-high-grade gold largely relies on empirical observations from structural and geochemical patterns in specific deposits, with no universally applicable indicators available. Progress is constrained by a limited and fragmented understanding of the geological processes responsible for forming ultra-high-grade gold ores and coarse gold nuggets. Despite significant advances in the study of gold mineralisation, no integrated synthesis of these enrichment processes has been undertaken. In this work, we review the scientific context and the prevailing hypotheses concerning the mechanisms that generate ultra-high-grade, nuggety gold deposits. We propose that extreme enrichment may result from a combination of localised processes, including: (i) novel modes of gold transport such as nanoparticles; (ii) viscoelastic fracture development, (iii) precipitation mechanisms linked to fluid–rock reactions, mixing of fluids, pressure–temperature variations, or piezoelectric effects; (iv) deposition and remobilisation through polymetallic melts; and (v) upgrading within deposits via processes such as piezoelectricity, nanoparticle aggregation, diffusion, and dissolution–precipitation reactions. In conducting this research, the occurrence of feedback loops linking the structural and geochemical is emerging as a common theme, where the structural record appears to have a direct impact on the geochemical processes underlying deposition of high-grade mineralisation.

O16.5

The role of pre-enrichment in the formation of orogenic gold deposits: insight from the Barsele deposit, Sweden

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Orogenic gold deposits have produced a large proportion of the world's gold supply. These deposits are structurally hosted in orogenic belts with mineralisation occurring in quartz veins and surrounding hydrothermally altered rock. A common feature of these deposits is the evidence of multiple mineralisation events such as reactivation of vein systems through many crack and seal events to form laminated veins. A further important process is early hydrothermal alteration that can optimize the host rock properties for mineralisation. Enrichment of gold during these early hydrothermal events would clearly be an important process in development of a large deposit.

We present the example of the Barsele orogenic gold deposit in the “gold-line” area of northern Sweden. The deposit comprises three distinct mineralized zones—Avan, Central, and Skiråsen—hosted within an 1.89-1.88 Ga early orogenic granodiorite. The rocks in the area were subsequently overprinted by c. 1.87 Ga and 1.80 Ga compressional events. Five different groups of quartz veins have been described; Qtz 0 to Qtz 4. Qtz 1 to Qtz 4 are planar quartz veins with similar characteristics and are interpreted to represent a single, main-stage veining event (Rann et al. 2019) utilizing late-orogenic brittle structures. The Qtz 0 veins however, exhibit irregular, worm-like morphologies, often with a distinct blue coloration, and are consistently cross-cut by all subsequent vein generations as well as by all structural elements, indicating an early orogenic timing. Qtz 0 veins are unique in terms of geometry, mineralogy, and associated metal content. Geochemically, they are distinguished by elevated Ti and Al concentrations relative to the other vein types and applying the titanium-in-quartz (TitaniQ) geothermometer developed by Wark & Watson (2006), yields temperatures of formation of $625 \pm 75^\circ\text{C}$ for these veins compared to temperatures of less than 350°C for the main stage veins (Rann et al. 2019). The Qtz 0 veins are interpreted to represent an early, high temperature magmatic-hydrothermal stage of mineralisation in the Barsele granodiorite. The bulk of gold is hosted in the late-orogenic main stage veins but the Qtz 0 veins play an important role in elevating the grade of the host rock intervals between the main stage mineralisation. Re-activation of early orogenic structures may have further controlled the emplacement of these late-stage quartz veins, providing pathways for remobilization and local concentration of gold into younger vein systems.

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O16.6

Application of hyperspectral drill core scanning to define alteration zones: Examples from the Suurikuusikko and Helmi gold deposits, the Central Lapland Greenstone Belt, Finland

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Alteration minerals are important for understanding and exploring hydrothermal ore deposits. Visual observation may not identify fine-grained minerals or define important compositional variations. Drill core hyperspectral imaging (HSI) system used in this study measures reflected light in the visible–near (VNIR, ~400–1000 nm), shortwave (SWIR, ~1000–2500 nm), and thermal infrared (TIR, ~8000–12,000 nm) ranges. Many minerals have diagnostic absorption features in these spectral regions, enabling their identification and mapping. Although sulphides do not have diagnostic features in these ranges, important hydrothermal alteration minerals such as white and dark micas (e.g., muscovite, chlorite, biotite) and carbonates exhibit distinctive features in the SWIR, while quartz, feldspars, many silicates, and carbonates can be mapped in the TIR. Furthermore, compositional changes in micas and carbonates that are invisible to the naked eye can be detected. Mineral maps and spectral parameters also help define lithological units, alteration zones, and, overall, the understanding of hydrothermal systems and vectoring toward ore deposits.

Operationally, hyperspectral core scanning is rapid; about 200 boxes can be scanned in one eight-hour shift. Captured high-resolution RGB imagery (100 µm resolution) and spectral data (1–2 mm resolution) form a digital archive. These datasets can be integrated with other geoscientific information such as geochemistry, geophysics, and structural data. Additionally, the permanent digital record ensures that core data remain accessible for future reinterpretation, even if the physical core is lost.

The Suurikuusikko (Kittilä Mine) and Helmi gold deposits are orogenic gold deposits hosted in the Kittilä Group rocks, metamorphosed under greenschist facies conditions and located in the Central Lapland Greenstone Belt. Suurikuusikko host rocks are dominantly intensely deformed mafic volcanic rocks, and the ore is refractory, with most of the gold hosted in arsenopyrite and pyrite. Based on visual core logging, gold mineralisation is associated with intense pre-gold albite and syn-gold carbonate–sericite alteration. Toward ore zones, HSI revealed changes marked by the disappearance of epidote, variations in carbonate, white mica and chlorite compositions, and variable sericite, silica, and albite abundances in proximal zones.

In the Helmi deposit, mineralised intervals are mainly hosted in the Savukoski Group—altered, sheared, and/or brecciated mafic and ultramafic rocks and tuffites—structurally intercalated with Kumpu Group conglomerates and sandstones. Mineralisation is associated with fine-grained pyrite as disseminations, intrafolial sulphide, or within narrow quartz–magnetite veins. In Helmi, it was also possible to map mineralogical changes toward the ore zone. The first observed change was the disappearance of epidote, followed by variations in the abundances and compositions of carbonate, chlorite, and white mica.

O16.7

Application of stratigraphy-controlled geochemical data analysis in Au prospective mapping in glaciated terrain

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Till is preferred media for sampling in glaciated terrains. Especially, in Finnish Lapland within the ice divide zone. Within the ice divide zone, a term 'weathered bedrock till' is sometimes used (Hirvas 1991). This refers to the debris being derived from the underlying weathered bed rock. However, the influence of till stratigraphy in mineral exploration is rarely investigated. Six till beds (till bed I–VI) have been described from the Lapland area (Hirvas 1991). Till element concentration values from the line till data set (Gustavsson et al. 1979) were used to investigate the stratigraphy for the purposes of gold exploration in the Kittilä area in central Lapland.

Two different methods for gold exploration were used a) one-meter intervals and b) statistically derived intervals. In the first method, each interval was one meter long starting from 0 m mark and continuing until 4 m mark. Four-meter depth was decided based on the average depth of till beds in the study area, which is about 2 meters (Hirvas 1991). The used data set (line till data set) further reinforced this with 2.08 m average. In the second approach, statistical methods were used. Here, the element concentration changes with depth were used. Particularly, identifying depth intervals where significant change in mean/variance can be found. All elements were first transformed into isometric log ratios (ilr). Elements Si, Fe, and Mg were used to define the interval breaks. After interval separation fuzzy logic (Zadeh 1965) was used. For fuzzy maps Cu, Ni, Co, Cr, Fe, Ca, and Mg were used.

As a result, eight maps were generated using fuzzy logic. Four maps for each approach. Receiver operating characteristics (ROC) (Obuchowski 2003) and area under the curve (AUC) were used to test which model was the 'best'. The results showed that the statistical method was better based on the AUC values calculated. For the statistical method intervals 0.4–1 m, 1–1.7 m, 1.7–3.6 m, and 3.6–10 m were deduced. For these AUC values 0.55, 0.522, 0.632, and 0.721 were calculated, respectively. Of these four the interval 1.7–3.6 m was decided to be the best for gold exploration, further this interval corresponds to till bed III. This is due to the lack of points within the 3.6–10 m interval, even though this interval had the largest AUC value.

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O16.8

Unraveling the origin of breccia-hosted Vähäjoki Fe-Co-Cu-Au deposit

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The Vähäjoki Fe-Co-Cu-Au deposit, located in the Paleoproterozoic Peräpohja Schist Belt of northern Finland, was discovered in the late 1930s. Despite its early discovery, only a few scientific studies have been published on the deposit to date (Liipo & Laajoki 1991; Niiranen 2005), and a comprehensive genetic model has remained elusive. This study presents the most up-to-date characterization of the Vähäjoki deposit, conducted as part of the EU funded REPower-CEST project (n:o 151, P5C1I2, NextGenerationEU).

The Vähäjoki deposit comprises over ten magnetite bodies, with a total iron resource of 10.5 Mt at 39.4% Fe (Mineral Deposits 2025). Several of these magnetite bodies are Co-Cu-Au mineralized exhibiting grades of 0.03–0.5% Co, 0.05–1% Cu, and 0.5 g/t Au. The deposit is hosted within an extensive (>10 km²) breccia system, predominantly developed in dolomitic marbles of the Rantamaa formation, part of the 2.13–2.05 Ga Tervola group. Mineralization occurred in a multistage system. An early magnetite-biotite-chlorite (K-Fe) stage was overprinted by a later sulfide (Co-Cu-Au-S) stage, the latter resulting in the precipitation of pyrite, cobaltite, chalcopyrite, arsenopyrite, pyrrhotite, and native gold. The sulfide stage was accompanied by the growth of unoriented amphibole porphyroblasts on the earlier K-Fe assemblages. Geochemical data indicate that the early stage introduced Fe, K ± Rb, and V into the system, while the later sulfide stage is characterized by a distinct element association: Ag-As-Au-Bi-Co-Cu-Mo-Sb-S-W ± Te, U.

The U-Pb age data of monazites and xenotimes record different stages of the Svecofennian orogeny between 1.93 Ga and 1.78 Ga. The sulfide stage is dated to 1.80–1.78 Ga, while the K-Fe stage likely occurred around 1.93 Ga. Sulfide deposition took place during the late stages of the Svecofennian orogeny, consistent with ages reported for several gold deposits in both the Peräpohja Schist Belt and the Central Lapland Greenstone Belt. The age of magnetite deposition suggests formation during the initial compressional phase of the Svecofennian orogeny.

The geological setting, geochemical signature, and trace element composition of magnetite and pyrite from Vähäjoki are consistent with an Iron Oxide Copper Gold (IOCG) classification. However, the significant age gap between the magnetite and sulfide stages presents a challenge to conventional IOCG models.

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O16.9

Gold mobility in subduction zone: Insight from the Cyclades Blueschist Unit

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Arc environments are locally gold-endowed (e.g. Au-rich porphyry, epithermal, skarn or VMS deposits) and it has been long hypothesized that gold mobilization during slab dehydration could affect the mantle composition and gold fertility during arc magmatism (McInnes et al. 1999; Tassara et al. 2022). In this study, we investigate gold mobility during prograde high pressure-low temperature metamorphism using metasedimentary and metavolcanic rocks from the Cycladic Blueschist Unit within the Hellenic subduction orogen. The Cycladic Blueschist Unit has sustained peak metamorphism from greenschist to upper-blueschist/eclogite facies and rocks showing all metamorphic facieses have been sampled on the islands of Santorini, Ios, Naxos and Syros (Greece). This sample collection with progressively increasing metamorphic grade allows to characterize large-scale gold mobility within a subduction zone. Whole rock geochemistry associated to ultra-low detection of gold by LA-ICP-MS on pressed powder pellets shows that gold is significantly mobilized by fluids at the upper-blueschist/eclogite metamorphic facies transition. Exhumed mélange zones from Syros provide insights in the behavior of gold at the slab-mantle interface and its fate in the mantle. While gold is locally enriched in metasomatic sulfides in mélange zones, it shows low gold content (0.72 ppb) relative to mantle values (ca. 1 ppb), suggesting that most of the gold is mobilized by subduction fluids, either travelling upslope along the slab-mantle interface (Kawano et al. 2011), or migrating within the mantle wedge (Wilson et al. 2014). In the later case, metasomatism may increase the gold fertility of the mantle, favoring formation of gold-rich deposits during later mid-crustal to shallow magmatic-hydrothermal processes.

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O16.10

Alteration and geochemical zonation at the Åkulla Au-Te deposit, Skellefte District, Sweden.

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The Åkulla Au-Te deposit exhibits a distinct alteration pattern and ore style in the VMS-dominated, Paleoproterozoic (1.9 -1.8 Ga) Skellefte District, Sweden. From production start in 2012 to the end of 2024, total mineral reserves and resources (including inferred) of the Åkulla Au-Te deposit sums up to 11.8 Mt of ore, grading 4.1 g/t Au, 7.7 g/t Ag, 150.0 g/t Te, 89.7 g/t Bi and 1.0 wt% S (Boliden 2024 and internal reports). The deposit is hosted by a volcanic and hydrothermal breccia complex of dominantly dacitic composition with a zoned quartz-topaz-aluminosilicate-rich alteration, Au-Te-Bi enrichments and paucity of sulfide. There are four styles of mineralization composed by native Au and a range of tellurides. Using a geochemical dataset of more than 100,000 assays and lithogeochemical data we describe the geochemical distribution relative to the mineral association at the Åkulla Au-Te deposit, investigate the nature and conditions of the Åkulla ore-forming system. The alteration zonation in the deposit shows an intensely leached quartz±topaz-dominated core that is depleted in most major cations including Al, is sulfide-poor and enriched in Si, Au, Ag, Te, Bi, Sb and Mo. Similarly to nearby VMS deposits, the outer zones are dominated by a chlorite-muscovite-andalusite alteration mineralogy, which are enriched in sulfide mineral. The zoned distribution of alteration minerals and chemical elements are interpreted to be controlled by progressively increasing pH and decreasing temperatures of the hydrothermal fluid outwards from the core of the deposit. Similarities of these element zonation patterns can be found in magmatic-hydrothermal mineral systems (Halley et al. 2015). The breccia complex is interpreted to have formed during crustal extension in a subaqueous and subsurface environment (Nordfeldt 2025). Formation of the breccia complex, hydrothermal system and mineralization are interpreted to be coeval, followed by regional deformation, metamorphism to upper greenschist facies and tilting to current orientation. The geochemical distribution in relation to the mineral associations suggests that the Åkulla Au-Te deposit formed as a syn-volcanic magmatic-hydrothermal system, representing a high-temperature magmatic end-member of the VMS deposit spectrum within the Skellefte District.

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O16.11

Metamorphic remobilization of precious metals at the epithermal Haile deposit, South Carolina, USA

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The Haile deposit, South Carolina, is a high-tonnage, low-grade, pyrite-dominated, Au-Ag, low-sulfidation epithermal deposit hosted in the Carolina terrane, South Carolina, U.S.A. and formed during the Neoproterozoic. During the Ordovician Taconic orogeny greenschist metamorphism resulted in internal remobilization of sulfides and precious metals. Here, we characterize both physical and chemical remobilization processes using textural, compositional, and micro-structural data on pyrite, native gold and tellurides.

Of the three pyrite types (Py1a, Py1b, Py2) identified, Py1a and Py1b were formed syn-genetically during the Neoproterozoic. Arsenic, precious metals and critical metals were incorporated into the pyrite structure syn-genetically (Neoproterozoic) with up to 2.49 wt% As, 103 ppm Au, 482 ppm Sb, and 145 ppm Te. Py2 was formed syn-D2 or post-D2 of the Ordovician Taconic orogeny as newly crystallized, coarse, subhedral to euhedral pyrite around porous anhedral Py1b by metamorphic fluids. Trace element contents are overall at least a magnitude lower in Py2 compared to the older syn-genetic pyrite.

During the Taconic orogeny, all three pyrite types experienced crystal-plastic and brittle deformation, albeit to different degrees: (1) low misorientation angles as a result of dislocation climb are preserved in strongly deformed Py1b and Py2; (2) higher abundance of high misorientation angles is common in most Py1a and Py1b that overprints foliation; (3) cataclastic cracks only occur in Py1b and Py2 and can have native gold and tellurides along these microfractures; and (4) annealed aggregates occur in all pyrite types but are most prominent in Py2. Physical remobilization was accompanied by chemical remobilization which was driven by coupled dissolution reprecipitation reactions between porous Py1b and metamorphic fluids and resulted in the liberation of precious and critical metals. The liberation and transport of precious and critical metals was enhanced by pores and cataclastic cracks in Py1b; however, their absence in Py1a prevented the liberation of these metals resulting in the absence of native gold and tellurides in or along Py1b.

Although remobilization is a local process and occurs at the micro-scale, it impacted all ore zones at Haile and played a major role in refining and upgrading the precious metal tenor of the deposit.

P16.1

Age and genesis of the high metamorphic grade Kultanummi gold prospect, southern Finland

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Kultanummi gold prospect is located in the Uusimaa belt, southwestern Finland. It is untypical prospect as it occurs within a high metamorphic grade terrain, the host rock being a migmatized paragneiss, and by its unusual alteration mineralogy, cordierite-sillimanite $\pm$ tourmaline $\pm$ rutile assemblage. These facts hamper the interpretation of the age as well as the genetic type of the deposit.

The purpose of this work was to study the age of fluid activity, alteration and gold precipitation in Kultanummi deposit and correlate these events to the regional geological evolution. Special interest was in interpretation of the peculiar alteration mineralogy as its age holds the key role when defining the genetic type of the deposit. Several thin sections were prepared from the location, which were scanned by SEM at Geological Survey of Finland (GTK) to identify minerals suitable for dating purposes. This was followed by in-situ U-Pb age determinations on zircons, monazites and rutiles at GTK. Based on the results, several age populations were found from Kultanummi. Firstly, zircons yielded ages related to the early Svecofennian evolution approximately at 1.88 Ga, which is interpreted as the age of the partial melting in the area. This is considerably older than the regional metamorphic peak at 1.82 Ga within the Uusimaa belt. Secondly, monazites also show some ages related to this ca. 1.88 Ga event, but the two main populations yielded ages of 1.82 Ga and 1.79 Ga, which are correlated to the regional metamorphic peak event of the Uusimaa belt and subsequent hydrothermal activity, respectively. Thirdly, a single rutile population shows ages related to same hydrothermal event as the younger monazite population.

Alteration and gold in Kultanummi are closely associated with sillimanite and cordierite-rich lithologies and both features show strong structural control. Based on this and the age results we suggest that Kultanummi represents an orogenic gold deposit with Al-rich fluid. Sillimanite and cordierite are considered to be alteration product by the Al-rich fluid, and this fluid activity is interpreted to have occurred slightly after 1.80 Ga.

P16.2

KOmatiite METamorphic devolatilization and METal mobilization (KOMET²): Implications for orogenic gold deposit formation

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Orogenic gold deposits are extensively studied as they account for more than 25% of the global gold supply. These deposits are found along a crustal continuum, from granulite to prehnite-pumpellyite facies rocks. The metamorphic devolatilization of metasedimentary and metavolcanic rocks at the greenschist-amphibolite facies transition is widely acknowledged as the primary source of fluids and metals for orogenic gold deposits up to amphibolite facies. At temperature above 600°C, however, this model is challenged as fluids may induce partial melting of quartz-feldspath-bearing rocks, consuming the fluids and preventing formation of deposits. Recent modelling suggests that komatiite — a significant but overlooked lithological unit in Precambrian greenstone belts — may generate auriferous metamorphic fluids up to the granulite facies and contribute to orogenic gold deposit formation.

The aims of KOMET² are to: 1) test the metamorphic devolatilization model applied to komatiite and investigate auriferous fluid production, 2) evaluate the contribution of komatiite devolatilization to orogenic gold deposit formation.

To achieve these aims, we will investigate metakomatiites in the Southern Cross and Kalgoorlie auriferous greenstone belts in the Yilgarn craton in Western Australia. By combining the mineralogy, whole rock geochemistry and thermodynamic P-T-X models of granulite to greenschist facies metakomatiite, we will characterize the behavior of metals, metalloids and ligands (e.g., As, Au, C, Co, Cu, Mo, Ni, Pt, S, Sb, Sn, Te) during prograde metamorphism and determine if an auriferous metamorphic fluid is produced. Orogenic gold deposits will be investigated to determine the link between metakomatiite devolatilization and ore formation.

P16.3

Tracing fluid sources in typical and atypical orogenic gold deposits using boron isotopes: Case-study from the Pohjanmaa Belt, Finland

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Orogenic gold deposits locally show anomalous enrichment in base metals such as Cu, Co, Ni, and in some cases, Sb, U and rare earth elements in addition to gold. These deposits are referred to as orogenic gold deposits with atypical metal associations. Gold in typical orogenic gold systems is transported by reduced, low-salinity hydrothermal fluids during metamorphism, carrying gold as hydrosulfide complexes. In contrast, base metals such as Cu and Co require more oxidized, high-salinity fluids capable of forming chloride complexes. The presence of evaporites in metamorphic belts appears to be important for Co mobilization and was suggested as potential fluid and ligand source for atypical orogenic gold deposits in the Peräpohja belt (Raja Au-Co deposit) and the Kuusamo belt (Au-Co Juomasuo deposit).

The Pohjanmaa Belt (PoB) in western Finland hosts both typical Au-only and atypical Co-rich orogenic gold deposits. However, there are no metamorphosed evaporites known in the PoB; and the mechanisms controlling base metal enrichment along with gold remain poorly understood. Remarkably, these contrasting deposit types occur within the same structure and similar host rocks, providing an opportunity to investigate the parameters affecting their varying metal enrichment. This study compares the Laivakangas and Huhta Au-only deposits with the Jouhineva (Au-Cu-Co-Ag) and Kurula (Au-Co) deposits. The deposits formed in two successive events: an initial As-Au-(Co-Ni) event, followed by a subsequent sulfide Cu-Au event. Hence, a possible explanation for the local enrichment in Co at Jouhineva and Kurula may be local differences in the mineralizing fluid.

As metamorphic fluid chemistry is buffered by the source rock, analysing boron isotopes ($\delta^{11}\text{B}$) of hydrothermal alteration minerals (tourmaline, biotite, amphibole) in-situ by LA-ICP-MS can fingerprint potential fluid sources and assess whether contrasting metal associations reflect differences in fluid origin or, for example, the addition of a magmatic-hydrothermal component, as shown for the Raja Au-Co deposit. A magmatic contribution is unlikely in the present study area due to temporal constraints, but nearby ultramafic rocks at the atypical Jouhineva deposit may represent a potential cobalt source. This could lead to isotopic variations from light $\delta^{11}\text{B}$ values ($< 0\text{‰}$) expected for metamorphic fluids from devolatilized metasedimentary or metavolcanic rocks, towards heavier signatures ($> 0\text{‰}$) typical of ultramafic rocks such as serpentinites. $\delta^{11}\text{B}$ values may also identify the influence of hidden evaporitic components.

O17.1 (Keynote)

Craton reconstructions and mantle plume tracks in deep time, with particular relevance to "greater Karelia"

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Of the ~35 preserved Archean cratons around the world, most if not all are fragments, or fragments of fragments, of late Archean "supercratons", i.e. the larger landmasses to which these craton fragments trace their ancestry (Bleeker 2003). At least two large independent supercratons, "Superia" and "Sclavia", named after their well-preserved internal fragments, had formed by the late Archean and underwent progressive breakup during the early Paleoproterozoic, from ca. 2.2 Ga to 1.9 Ga. Based on well-populated apparent polar wander paths, these supercratons moved independently, and, hence, the mythical notion of a single, long-lived, late Archean supercontinent "Kenorland" cannot be correct, aside from being untestable.

Craton fragments can be correlated and put back together again by matching distinctive basement geology, by correlating pre-breakup epicontinental basin remnants, and by correlating pre- to syn-breakup large igneous provinces, particularly their dyke swarms. Large dyke swarms, being vertical and intruding far back into cratonic hinterlands, are relatively insensitive to uplift and erosion. They provide robust piercing points, can be precisely dated, and can yield high-quality paleopoles.

Of all the dispersed Archean cratons, more than 10 trace their origin back to supercraton Superia, representing "nearest neighbour" fragments to the large Superior craton: Karelia, Kola, Wyoming, Hearne, Kaapvaal, Pilbara, Yilgarn, Zimbabwe, Sask, North Atlantic craton, and possibly Dharwar. Kaapvaal-Pilbara, as part of a large ancient superterrane that also included Wyoming, joined a growing Superia late in the game at ca. 2660 Ma, separating again ~700 Myr later, leaving the ancient Minnesota River Valley terrane behind. "Greater Karelia" may also have been part of this ancient superterrane. Yilgarn is best matched, belt-by-belt, to the western side of the Superior. Wyoming and Hearne broke off Superia as one piece and should be viewed as a single craton.

With a robust reconstruction of Superia, other important new insights follow, including on ancient mantle plume tracks. Here we present evidence for two major plume tracks, both starting within Superia's core, one at 2480 Ma ("Matachewan track"), the other at 2125 Ma ("Marathon track"). The Matachewan plume track is particularly relevant to the position of Karelia within supercraton Superia (Davey et al. 2020) and spawned some of Europe's largest mafic layered intrusions. The Marathon plume track, after crossing over into then-contiguous Kaapvaal, first spawned 2060 Ma carbonatites (e.g., Phalaborwa), before culminating with the emplacement of the Bushveld Complex at 2056 Ma.

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O17.2

Timing and Evolution of Archaean Crust: Constraints from Lake Inari, Arctic Fennoscandia

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Understanding the origin and evolution of Earth's earliest continental crust is a fundamental challenge in Earth Sciences, with broad implications for early tectonic regimes and the conditions that governed the Earth's surface environment. Constraining Archaean crust-formation processes requires integrated geochemical and geochronological studies of granitoid suites. Tonalite–trondhjemite–granodiorites (TTGs), which dominate the preserved Archaean felsic crust, display two geochemical endmembers distinguished by their heavy rare earth element (HREE) content: low-HREE and high-HREE TTGs. While the general formation of TTGs has been linked to dehydration melting of basaltic crust, the origin of the distinct TTG types and their temporal and genetic relationships remains a topic of active debate. Here, we present new U–Pb zircon ages from low- and high-HREE TTGs and associated porphyritic granitoids in the Lake Inari terrain, Arctic Fennoscandia, to resolve their temporal and genetic relationships. Our results reveal a prolonged interval of migmatization spanning between 2900 and 2600 Ma, reflecting sustained thermal input over hundreds of millions of years, likely driven by a long-lived mantle plume beneath a stagnant or sluggish-lid tectonic regime. The overlapping zircon ages and proximal field relationships of high- and low-HREE TTGs indicate derivation from a common source rather than formation in distinct tectonic settings. Subsequent prolonged melting of thickened felsic crust produced porphyritic granites between 2650 and 2500 Ma. Minor zircon recrystallization associated with the ~1.9 Ga Lapland-Kola orogeny did not alter the Archaean migmatite structures. The Lake Inari TTGs peak around 2.8 Ga, approximately 100 Ma before the proposed assembly of the Kenorland supercontinent. These findings provide robust constraints on the timing, sources, and processes responsible for formation in Arctic Fennoscandia. They highlight the role of prolonged plume-driven thermal regimes in Archaean crustal evolution and offer new insights into tectonomagmatic conditions preceding early supercontinent assembly.

O17.3

Age of the Rommaeno complex – Bringing together data from the GTK archives

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Geological Survey of Finland has been accumulating a database on U-Pb ages for more than 60 years. Later, Sm-Nd and Pb-Pb isotopic analyses have been added to the national isotope archive. In light of the ongoing BiCo project (Birth of the Continents), that focuses on Archean crust formation in northern Finland, among other areas, we will take a look at the existing geochronology and isotopic data on the Archean Rommaeno complex in northern Lapland.

The Rommaeno Complex is located in the the Norrbotten Craton, and extends over the present-day northern Sweden and northwestern Finland. The area is very remote and rough terrain with few roads, and consequently, few samples have been collected from within the complex.

The oldest dated rocks in the area are two ~3215 Ga tonalitic gneisses close to the border between Finland and Sweden. The following dated event is represented by the metavolcanic rocks of the Ropi suite, with ages of about 2.93 Ga. The Ropi suite divides the Rommaeno complex TTGs into western and eastern groups. The composition of the metavolcanic rocks vary, the ages are from felsic and intermediate types

The next age is from Ailakkavaara rhyolite at the northwesternmost margin of the complex. The age is 2.84 Ga. Similar, although imprecise age has been obtained from a gneissic rock in Sweden (Skiöld 1979). The majority of the TTG rocks display ages from 2.76 to 2.72 Ga. These rocks represent a range of TTG-type gneisses to pure granites. In Sweden, ages of the tonalites and granites of the Råstojaure complex scatter between 2.69 and 2.67 Ga (Martinsson et al. 1999).

Whole rock Sm-Nd data exist on few samples from the Rommaeno complex. The initial epsilon values are mostly close to chondritic values. The only exception is the Ailakkavaara rhyolite, which has a Nd isotopic composition close to the depleted mantle value.

It should be noted, however, that sampling has been strongly biased along the main road 21 due to the challenging terrain. Within the BiCo project, we have collected several new samples representing various TTG and metabasalt types from the Rommaeno complex, and wish to shed more light into the petrogenesis of this Archean unit.

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O17.4

Geochemistry of Archaean basalts: global comparisons and case studies from northern Finland

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This presentation has two parts. First, we present our effort to build an up-to-date and comprehensive database of Archaean basalts from greenstone belts and those related to TTGs, compiled from published analyses. This integrated framework allows direct comparison with Phanerozoic basaltic suites using immobile trace-element ratios. Such comparisons enable us to evaluate both the reliability of Archaean datasets and the extent to which Archaean basalt geochemistry resembles that of Phanerozoic tectonic settings. Preliminary results indicate that Archaean basalts differ from modern arc compositions but share similarities with Phanerozoic oceanic and continental flood basalts, with systematic changes evident from the Eoarchaeon to the Neoarchaeon. The second part presents a petrographical and geochemical comparison of TTG-related metabasalts from Arctic Fennoscandia that gave origin to the tonalite–trondhjemite–granodiorite suites (TTGs) of the Rommaeno and Inari Lake complexes. While similar in field appearance, these metabasalts reveal distinct geochemical signatures. The Rommaeno metabasalts preserve enriched trace element patterns comparable to flood basalts, whereas the Inari metabasalts display highly variable and overprinted compositions, likely reflecting either stronger metamorphism, higher melt extraction, secondary alteration; or all of these processes. Future work will expand the metabasalt dataset and apply isotopic systematics to better constrain the tectonic settings and mantle sources of Archaean basaltic precursors to TTG magmatism.

O17.5

Neoproterozoic crustal growth – an isotopic perspective from the Lewisian Complex

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Primarily a product of Neoproterozoic crustal growth, TTG suite gneisses exposed across the Lewisian Complex of northwest Scotland have long provided a natural laboratory for studying crust-mantle differentiation using radiogenic isotopes ever since the first recognition of their antiquity in the late 1950's. Furthermore, the Lewisian occupies a key position relative to the Fennoscandian Shield and the North Atlantic craton in Greenland and Labrador, as evidenced by likely correlative ca. 1.9 Ga supracrustal belts occurring across the region (Park 1994).

The chronological framework of the Lewisian was established several decades ago using bulk rock radiogenic isotope systematics (Rb-Sr, Sm-Nd and Pb/Pb), supplemented later by single zircon U-Pb studies. These revealed diachronous crustal growth across the exposed Lewisian between ca. 3.0 and 2.8 Ga, followed by high-grade, in places granulite facies, metamorphism at 2.7 and (locally) 2.5 Ga. Recent high spatial resolution U-Pb geochronological investigation of zircon from the Lewisian TTG gneisses (Whitehouse & Kemp 2010; Whitehouse et al. 2022) has further refined the timing of crustal generation, with complementary Hf isotope measurements in dated zircon proving constraints on the probable evolution of the ultimate mantle source to the TTG precursors. Notably, over a ca. 400 Ma period from ca. 3.1 to 2.7 Ga, the TTG gneisses have initial Hf isotope ratios that are chondritic to only slightly suprachondritic. Derivation of a TTG source rock from conventional MORB depleted mantle (DM) results in crustal residence times considerably in excess of the TTG crystallisation ages, which is geodynamically implausible. Instead, a mildly depleted mantle tapped at regular intervals a few 10s of Ma prior to TTG generation seems more likely and, furthermore, is consistent with observations from couple U-Pb and Hf studies of zircon across Fennoscandia and Greenland (see Petersson et al. 2024). This, while not necessarily global in extent, such a mildly depleted mantle source appears to be at least regionally extensive on a super-continent scale and its possible existence in other regions should be assessed before construction of crustal evolution models for local TTG suite rocks, as well as global crustal growth curves based on Hf isotopes in detrital zircon.

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O17.6 (Keynote)

The Birth of Continents (BICO): Insights from Archaean terrains in Arctic Fennoscandia

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The origin of Earth's earliest continents is one of the most fundamental debates in geology. The Birth of Continents (BICO) consortium, funded by the Research Council of Finland (2025–2029), addresses this by investigating Archaean tonalite–trondhjemite–granodiorite (TTG)–basalt associations in the Lake Inari terrain and the Rommaeno and West Troms complexes of Arctic Fennoscandia. These rocks preserve structural evidence of partial melting – melt segregation, extraction, migration, and redistribution – offering key insights into how the first continental nuclei formed. We hypothesise that TTGs did not develop as rising plutons but through intracrustal partial melting (migmatization) of basaltic protocrust heated by long-lived, stationary heat sources. As the melt fraction increased, the protocrust progressively weakened. Once a critical threshold was exceeded, the crust completely lost coherence, and the resulting TTG mush, with incorporated basaltic remnants, crystallised into buoyant continental nuclei. To test this model, BICO combines field geology, optical and SEM petrography, isotope and elemental geochemistry, mineral chemistry (element partitioning), geochronology, and rheology. A major innovation is the “melt-o-meter,” which integrates zircon 3D X-ray computed tomography, melt inclusion analysis, and Zr isotope thermometry to quantify degrees of partial melting. Led by Finnish institutions and collaborating with colleagues in Sweden, Norway, the UK, and Australia, BICO aims to establish a reference terrain for TTG–basalt relationships and refine models of Archaean crustal growth.

O17.7

New finding of extensive 2.44 Ga Granitoid Magmatism Associated with Layered Intrusions in Northern Fennoscandia

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Northern Fennoscandian shield contains layered intrusions related to the rifting event at ca. 2.45 Ga. Typically, and also in Fennoscandia, anorogenic layered intrusions are accompanied by coeval felsic magmatism. The bedrock between the Koillismaa and Näränkävää layered intrusions in northern Finland has been the subject of geophysical investigations for several decades. These studies have revealed an extensive positive magnetic and gravity anomaly in the area. To further constrain the source of this anomaly, the Geological Survey of Finland drilled almost vertical drillhole to a depth of ca. 1.7 km. The drilling intersected mafic–ultramafic rocks, which are the source of the observed geophysical anomaly, at around 1.4 km depth.

This study focuses on the felsic rocks encountered above and within the mafic–ultramafic units. The first 1.4 km of the borehole consists of TTG-series tonalites (intruded by leucogranitoid dikes) and large amounts of homogeneous Early Paleoproterozoic granitoids, as well as cross-cutting diabase dykes. Petrographic analyses of the granitoids show that granophyric intergrowths are widespread near the contacts with leucogranitoid dikes and diabase. Early Paleoproterozoic granitoids, were identified to be crosscutting the Paleoproterozoic mafic intrusives. The Early Paleoproterozoic diabases are geochemically similar to nearby calc-alkaline mafic dike swarms and yielded an age of 2426 ± 3 Ma. The unpublished age U–Pb determinations from the Paleoproterozoic granitoids and related quartz diorites yielded overlapping ages around 2.45–2.43 Ga (2426 ± 3 Ma, 2455 ± 5 Ma, 2457 ± 6 Ma, 2450 ± 5 Ma, 2440 ± 11 Ma, 2436 ± 11 Ma). The Early Paleoproterozoic granitoids are reddish, fine-grained, and contain magnetite and ilmenite. Their A-type geochemistry is marked by high SiO_2 (66.9–74.8 wt%), elevated $\text{K}_2\text{O}/\text{Na}_2\text{O}$ (~ 1.15) and $\text{FeO}t/(\text{FeO}t+\text{MgO})$ (0.68–0.84), and low CaO (median ~ 1.6 wt%).

Our objective is to model the evolutionary processes governing granitoid magma genesis. We hypothesize that this evolution was driven by partial melting of Archean granitoid wall rocks, triggered by heat input from mafic–ultramafic layered intrusions. The model will also take into account the possible interaction between the mafic and felsic magmas. Importance of the Archean crust in magma genesis is supported by whole-rock Sm–Nd isotope data, with the initial ϵ_{Nd} values ranging from -7.2 to -3.5 for the Early Paleoproterozoic granitoids. This new finding provides a novel research target to study the widespread bimodal magmatism and heat input known from the northern Fennoscandian Shield.

O17.8

Pasalanmäki complex, Central Finland, a new addition to the pedigree of the Lower Svecofennian (1.93–1.91 Ga) magmatic rocks

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This study combines results of bedrock mapping, thin section studies, whole-rock geochemistry, whole-rock Sm-Nd analyses and zircon single grain age determinations to characterise the previously poorly studied Pasalanmäki complex in Central Finland located within the Raahe-Ladoga Suture.

The dominant rock types of the 10 km long and 2.5 km wide complex are biotite-hornblende tonalites and variably migmatitic biotite-hornblende gneisses. The groups have similar geochemical characteristics (calc-alkaline, ferroan, intermediate to acidic) and are interpreted to represent plutonic and volcanic rocks from the same magmatic event taking place in a magmatic arc. Tonalites and gneisses were later intruded by mafic magmas, interpreted as belonging to the 1.88 Ga Ni-potential Kotalahti suite. However, no indications of ore potential intrusions were found in the study area. All of the above-mentioned rocks are crosscut by biotite granite dykes and small intrusions interpreted as part of the 1.87 Ga Haukivesi suite.

The single grain zircon ages from all samples display significant scatter which is attributed to lead-loss during active deformation along the Raahe-Ladoga Suture under high temperature conditions. Initial ϵNd -values of the tonalites and gneisses are distinctly lower (-1.6, -2.6 and -7.2, $t=1.91$ Ga) and depleted mantle model ages older (2.09, 2.27 and 2.87 Ga) than previously reported for Lower Svecofennian magmatic rocks which have positive initial ϵNd -values and depleted mantle model ages close to 2.0 Ga.

Based on the field evidence, geochemical data, mantle model ages and zircon U-Pb age determinations we interpret the tonalites and gneisses to be part of the Lower Svecofennian 1.93–1.91 Ga magmatism. The Sm-Nd data requires significant contribution from, or contamination by, material with prolonged crustal history, we propose that in the case of the Pasalanmäki complex this contribution was from Archean crust.

Pasalanmäki complex is located in a transpressive left-stepping bend in the dextral Airaksela shear zone. Structurally the area is dominated by NW-SE striking shear zones with prolonged activity lasting until ~ 1.80 Ga.

O17.9

Geochemical structure, age and petrogenesis of the A-type Mesoproterozoic Karlshamn pluton, Blekinge, southern Sweden

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The Karlshamn pluton which intruded at ca. 1.45 Ga in southern Fennoscandia contains two major coeval suites. Both of these have A-type affinity and consist of metaluminous, ferroan, alkali-calcic, and very-high K (shoshonitic) granitic rocks. The two suites are geographically separated within the pluton, and form (semi)parallel trends on Harker-type diagrams. The Eastern suite comprises quartz monzodiorite, quartz monzonite and granite while the Western suite mainly consists of monzogranites. Both suites exhibit similar chondrite-normalized REE patterns with relatively steep LREE and flat HREE. Aluminium-in-hornblende barometric and zircon-saturation thermometric estimates show that both suites were crystallized at relatively high temperatures of 850-900 °C and low pressures of 0.33-0.43 GPa.

Ion microprobe zircon dating from a monzonite of the Eastern suite yielded concordant to nearly concordant U-Pb isotopic compositions. The weighted average ²⁰⁷Pb/²⁰⁶Pb age is 1445 ± 11 Ma (2σ, MSWD 1.2), interpreted to date magmatic crystallization. The complex zircons from a monzogranite in the Western suite showed somewhat more scatter and slightly younger ages; however, there are no signs of older inherited materials and no significant age differences between the core-like domains and the overgrowths. The cores yielded a weighted average ²⁰⁷Pb/²⁰⁶Pb age of 1431 ± 20 Ma (2σ, MSWD 1.5) and the rims an age of 1424 ± 19 Ma (2σ, MSWD 4.2). The overall age of the zircons from the Western suite is 1426 ± 11 Ma (2σ, MSWD 2.6).

The two major suites as well as related leucogranites and mafic enclaves that are present mainly in the Western suite have indistinguishable initial ε_{Nd} values of -2.2 to -2.7. The Rb-Sr system shows some disturbances; however, initial ⁸⁷Sr/⁸⁶Sr ratios of undisturbed samples from the two major suites vary between 0.703 and 0.706. Two alternative models are proposed for the origin of the magmas: one where local crust of ca. 1.76 Ga age melted and mixed with intermediate magma that originated by fractionation of mantle basaltic melt, and another with melting of preexisting mafic lower crust.

The mafic enclaves are interpreted as cumulates formed along the walls of the feeder conduits by fractional crystallization caused by the temperature gradient across the feeder walls. The presence of these mafic enclaves in the Western but not the Eastern suite may indicate that they were formed from the Eastern suite magma and subsequently were picked up and engulfed in the later Western suite magma, using the same magma conduits.

Major element geochemical modeling indicates that the Eastern suite intruded first (in accordance with the age determinations) and that the remaining magma experienced around 20% of plagioclase fractionation before it intruded to form the Western suite. The vicinity of the Karlskrona deformation zone may have influenced the intrusion of the pluton.

Magmatic record of rapid trench retreat along the western Fennoscandian margin at ca. 1.65 Ga

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The growth and evolution of long-lived active margins rely largely on geochronological and isotopic data that provide constraints on the timing and duration of magmatic events and the proportions of reworked older crust vs. mantle-derived juvenile additions. Combined with geochemical data that inform on intensive (temperature, pressure) and extensive (water contents) properties of partial melting and melt evolution, detailed models of the tectonomagmatic evolution of an active margin can be established. Following the 1.9–1.8 Ga Svecofennian amalgamation of (proto) Fennoscandia, the western Fennoscandian margin grew oceanward until ca. 1.45 Ga above a dominantly east-dipping subduction zone. Initial active-margin processes formed the Transscandinavian Igneous Belt between 1.85 and 1.65 Ga, with isotopic compositions indicating variable juvenile crustal additions and reworking of Archaean crust. Between 1.65 and 1.45 Ga, the Gothian and Telemarkian orogenies are characterised by dominantly juvenile input, suggesting formation in island and continental arcs outboard of Fennoscandia. Here, we present new whole-rock geochemical and zircon U–Pb/Hf isotopic data from a suite of granitic and rhyolitic rocks in tectonic windows in east central Norway, near the Norwegian–Swedish border (Blåfjella–Skjækerfjella and Sylän). The granitic and rhyolitic rocks typically have $\text{SiO}_2 > 70$ wt.% and classify as ferroan. They are enriched in incompatible trace elements with strong negative Eu anomalies in chondrite-normalised diagrams and strong negative Ba and Sr anomalies in Primitive mantle-normalised plots. These features indicate relatively small-degree melting of lower-crustal rocks within the stability field of feldspar, suggesting relatively hot and dry melting, consistent with zircon saturation temperatures in excess of 800°C. The rocks yield ages between 1.665 and 1.645 Ga and have Hf isotopic compositions consistent with derivation from the surrounding 1.8 Ga crust. In contrast, coeval magmatic rocks farther west lack similar large whole-rock geochemical anomalies and have Hf isotopic compositions more in line with juvenile arc magmatism. We interpret the felsic magmatism at 1.665–1.645 Ga to reflect rapid, slab rollback-related trench retreat of the western Fennoscandia margin to a more outboard position, with subsequent magmatism lacking older crustal input. This interpretation marks a significant advance in our understanding of the evolution of the western Fennoscandian margin, but leaves questions regarding the timing and processes leading to accretion of this crust unanswered. Further work along the lines presented here, as well as constraining the timing of metamorphic and deformational events, is needed to answer these questions.

O17.11

First insights from regional Magnetotelluric investigations of the Wiborg Rapakivi Batholith

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The emplacement of the Rapakivi Granite batholiths in southern Finland marks the latest magmatic activity in the formation of the Finnish part of the Fennoscandian shield. The Wiborg Rapakivi Batholith has recently attracted interest for geothermal heat production because of its elevated heat flow and radiogenic heat generation compared to the surrounding bedrock.

As part of the Geonergialoikka project (<https://projektit.gtk.fi/geoenergialoikka/>) GTK has collected multiple regional and local geophysical datasets across the Wiborg Rapakivi batholith, including magnetotellurics (MT), seismic reflection profiles, gravity and petrophysical sampling. Here we report on first results from our regional MT study compared with first results from the reflection seismic profiles.

In Autumn 2024 and Spring 2025 66 5-channel broad band MT sites were collected along a corridor from Lahti to Virolahti. The site spacing of 5-7 km targets regional upper to mid crustal features. Data are characterized by exceptionally high resistivities of $10^6 \Omega\text{m}$ showing regions of largely unaltered, intact bedrock. Large induction vectors of magnitude 1 -2 indicate very high localized lateral resistivity contrasts. First inversions results shows high resistivities in the first 10 km as well as several narrow-elongated sub horizontal conductive features of $10 \Omega\text{m}$. The most prominent narrow conductor is E-W trending and aligning with the location of the first Salpausselkä at depth from 3-10 km, which may control the location of the glacialfluvial deposits. Another major conductive N-S oriented zone is below Kymijoki river. The intersection of both conductors is co-located with the Kouvola earthquake swarms.

Coinciding with MT survey extent, three 2D reflection seismic profiles were acquired (total of ~42 km). The resulting high-quality dataset reveals strong reflectivity patterns along profiles. The upper few kilometers within the WRB are mostly seismically transparent, with some sparse, short reflectors. A prominent reflective horizon is observed at ~8–10 km depth, deepening slightly southwards, may represent the base of the rapakivi granite. Beneath, a deeper reflectivity patters suggest lower-crust layering. Although the resolution of the MT and seismic datasets is not directly comparable, their images show a consistent structural trend and coinciding events.

The initial results of the geophysical investigation demonstrate the value of integrated geophysical imaging for constraining the geometry, internal structure, and physical properties of the Wiborg Batholith. Those provide new insight into crustal architecture in southeastern Finland and form a basis for evaluating the geothermal potential of rapakivi granites.

O17.12

Stairway to the upper mantle revisited – new modelling result of the Skellefteå electrical conductor

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Regional scale magnetotelluric (MT) investigations of the Fennoscandian Shield was initiated in the early 1980'ties and involved several measuring campaigns in the Nordic countries. The main results from measurements along the Fennoscandian Long Range Profile was the modelling of a highly conductive structure dipping towards NE and below the Skellefte Island Arc (Rasmussen et al. 1987). The interpretation involved the presence of the remnants of an early Proterozoic subduction zone. This interpretation was later confirmed by the reflection seismic data from the Babel experiment (Babel Working Group 1990)

The previous modelling of the MT data published in 1987 was based on a trial-and-error modelling approach in which 2D modelling responses were calculated and compared with the measured data. The rather coarse finite element modelling grid of the subducting part resembles a stairway to the upper mantle. The possibility of performing 2D inversion of MT data became available later and today 3D inversion of MT data is common. In addition, computer memory now allows a much finer discretization of the model space compared to the previous model.

Results of 2D and 3D inversion of MT data from the Skellefte area are presented. The data includes those modelled previously and complemented by so far unpublished data. The new modelling result confirms the previous interpretation of a subducting slab beneath the Skellefte Island Arc. A second NE dipping subducting slab is modelled beneath the Knaften Island Arc.

The conductivity models are discussed with reference to the North Atlantic Central Plain Anomaly and the Trans-Hudson orogen.

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O17.13

Regional 3D resistivity model of the Precambrian basement and overlying the Central Norwegian Caledonides

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A regional magnetotelluric dataset was collected during two field campaigns in 2022–2023 as a part of the D-Rex project (Deposit to Regional-scale Exploration). The aim of the ERA-MIN project is to identify regional-scale structural controls that are related to metal endowment in different subareas of Fennoscandia. The dataset is now inverted into a 3D resistivity model of the Caledonian nappes and underlying Precambrian basement.

The study area of c. 80 x 120 km was covered with more than 250 magnetotelluric broadband stations recording in the period range of 10^{-3} – 10^3 s and spaced each 5–10 km. The data quality is excellent, and the impedance tensors already reveal consistent 3D behavior.

The MT responses are inverted using the GoFEM software, which uses multi-scale adaptive meshes. These are needed to account for the variable topography as well as the highly conductive ocean and sediments that border the study area to the west.

The resulting 3D resistivity model reveals a complex three-dimensional electrical structure within and below the Caledonides. A pronounced conductivity anomaly is observed in the Precambrian basement at mid-crustal depths. It underlies the nappe stack where it is thickest, yet the relationship of the mid-crustal anomaly to the Caledonian structures remains unclear. Several smaller conductivity anomalies are located at upper crustal levels. A comparison with an independent estimate of the nappe thickness indicates that these anomalies may be either primarily within the Caledonian nappes or entirely underneath but rarely if at all cross the nappe-basement interface. Correlations of the intra-nappe conductors and near-surface conductive features with known Cu-Zn deposits are investigated. The nature of the deep conductivity anomalies is unknown but can point to ancient tectono-magmatic processes. To which degree these modified the crust and thereby provided structural control on the subsequent orogenic processes needs further investigation.

O17.14

Age determination and oxygen isotopes of baddeleyite cores in zircons – evidence of arclogite formation during the Svecofennian orogen

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Arclogites are igneous high-pressure garnet pyroxenite rocks, which are suggested to play a major role in the magma generation in modern continental arcs, hence contributing to the formation of continental crust and potentially provide the “missing link” between the composition of continental crust and parental magma. Arclogites are found in the roots of the thickest arcs, and they represent the residue (cumulates and/or restites) of the fractionation/partial melting processes that produce the prominent intermediate-felsic magmas of continental arcs in subduction-related systems. Arclogites tend to partially founder into upper mantle within 5–30 Myr cycles due to their higher relative density.

Kara et al. (2020) suggested a geodynamic model of arclogite formation at 1.89–1.87 Ga followed by (partial) foundering and partial melting of the arclogites at 1.86 Ga during the Svecofennian orogenic evolution. The model is based on several evidence: i) large volume of 1.89–1.87 Ga Fe-depleted felsic magmatic rocks, ii) occurrence of 1.86 Ga OIB-type mafic dykes, which were geochemically modelled to be partial melts of garnet-pyroxenite xenoliths found from kimberlite pipes in Eastern Finland (similar to arclogite xenoliths found elsewhere), iii) extensional tectonic setting at 1.86 Ga, iv) high crustal thickness and v) occurrence of high velocity lower crust beneath large areas of the Svecofennian orogen. A peculiar observation in the 1.86 Ga OIB-type rocks was that many of the zircons had baddeleyite cores. We have now dated and measured O-isotope composition of the baddeleyites by SIMS at the Swedish Museum of Natural History. The baddeleyites yielded ²⁰⁷Pb/²⁰⁶Pb ages between 1.91 and 1.85 Ga with a major cluster around 1.88–1.87 Ga thus being older than crystallisation age of the rock. The $\delta^{18}\text{O}$ values of the baddeleyites are extremely low and range between -4.8 and -1.5 with three outliers showing positive values. These contrast with the zircon $\delta^{18}\text{O}$ values between +5 and +6.8 of the same rock. We suggest that the baddeleyites crystallized in low-silica conditions during arclogite formation whereas the zircons represent transformation to silica and fluid enriched conditions after partial melting of the arclogites and during crystallisation of these partial melts.

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In-situ garnet Lu-Hf geochronology from contentious high-pressure rocks in northern Fennoscandia

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Orogenic eclogites are generally regarded as unambiguous indicators of subduction and their general emergence in the geological record at around 2 Ga probably reflects a combination of subduction into a cooler mantle and continental processes that facilitated preservation. In the context of eclogite emergence in the geological record, the formation of high-pressure rocks in the Belomorian orogenic belt in northern Fennoscandia has long been a subject of contention. There are several schools of thought. One is that high pressure metamorphism occurred at c. 2.7 Ga, and therefore represents a significantly older record of eclogite metamorphism compared to its general preservation from c. 2Ga. The other view is that high pressure metamorphism in the Belomorian Orogenic Belt occurred at around 2 Ga, and forms part of the global set of c. 2 Ga eclogites. Another is the rocks record two episodes of eclogite metamorphism.

A combination of sample-scale X-ray mapping and laser ablation ICPMS and Time-of-Flight mapping has been used to delineate two generations of garnet in a sample from the well-studied Stolbikha Island locality in the Belomorian Belt. The sample contains garnet and voluminous diopside-plagioclase symplectites whose re-integrated composition is consistent with the former presence of omphacite. The symplectites overprint hornblende that likely formed during high-pressure melt crystallisation. The cores of the older generation garnet are comparatively HREE rich, and give an in-situ laser ablation Lu-Hf age of 2490 ± 40 Ma. The second generation garnet is comparatively HREE depleted, and gives an age of 1875 ± 86 Ma. The comparatively large uncertainty of the younger garnet age determinations reflect the low Lu concentrations in the garnet. Both generations of garnet preserve partially relaxed major element zoning and given the generally understood relative diffusivities of major elements and Lu and Hf, it is probable both Lu-Hf ages are meaningful. An important difference between the garnet generations is the presence of rutile inclusions in younger garnet and their absence in older garnet. P-T modelling suggests c. 2.5Ga metamorphism occurred at c. 6-8kbar at temperatures $> 750^{\circ}\text{C}$. For the younger mineral assemblage, P-T modelling combined with Zr-in rutile thermometry from rutile-quartz-zircon clusters in c. 1875 Ma garnet, give c. 1.5 GPa and 700°C .

The results indicate high pressure metamorphism occurred at c.1875 Ma and overprinted an older garnet-forming metamorphic event at c. 2.5Ga characterised by comparatively high thermal gradients. We find no evidence for pressures $> 2\text{GPa}$ for metamorphism at c. 1875 Ma as suggested by some previous workers, or evidence for high pressure metamorphism at c. 2.7 Ga. The high-P metamorphism does not appear to be Neoproterozoic in age and instead belongs to the now globally distributed suite of Palaeoproterozoic rocks that records the transient emergence of eclogite during the initial stages of Nuna assembly.

The Lapland Granulite Belt: new Lu–Hf garnet dates and P–T results

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The Lapland–Kola Orogen comprises the Paleoproterozoic terranes of the Lapland Granulite Complex and Inari–Tersk arcs, which are sandwiched between Archean cratons. This crescent-shaped orogen extends across arctic Finland, Norway, and into Russia's Kola Peninsula, where eclogites are also present. Studied in detail initially by Eskola (1952), the Lapland Granulite Complex (LGC) in Finland comprises extensive garnet–sillimanite±cordierite metapelitic gneisses hosting mafic orthopyroxene-bearing sheet-like bodies. Anorthosites are associated with the complex to the west, and pegmatitic bodies cross-cut the granulites throughout. We present new field observations of the LGC and contact relations with adjacent units (focussing on the Ivalo, Deatnu, and Angeli areas). For a suite of samples, we present: (1) *In situ* Lu–Hf garnet dating (following the method of Simpson et al. 2021); (2) phase equilibria modelling using MAGEMin (Riel et al. 2022) utilising major element EPMA maps analysed with XMapTools (Lanari et al. 2014); and/or (3) Zr-in-rutile thermometry. *In situ* Lu–Hf garnet geochronology yielded ages for Lapland Granulite Belt granulites (1919 ± 16 Ma) and adjacent Kaamanen Complex gneisses (1919 ± 10 Ma) that are identical within uncertainty, and consistent also with previously-reported U–Pb zircon ages for the same region (1919 ± 3 Ma; Tuisku & Huhma 2006). LGC granulites experienced peak P–T conditions of 830–950°C at 6–8 kbar, with the rocks cooling and decompressing initially to ~750°C at ~4–6 kbar. Some of the modelled samples record ultrahigh-temperature (UHT; >900°C) conditions: a grt–sill–crd metapelite from Deatnu valley (940°C, 6 kbar), corroborated by Zr-in-rutile thermometry; and a grt–opx mafic granulite (marginal enderbite) also from Deatnu (950°C, 7 kbar). Tectonic models involving underplating by anorthosites and their source rocks, and lithospheric extension by slab rollback, will be explored as mechanisms for achieving these hot and widespread granulite-facies conditions.

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O17.17

Terrane provenance and collision-related metamorphism in the Lapland-Kola Orogen, northeastern Fennoscandian Shield

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Since Eskola's classic study of the Lapland granulites (Eskola 1952), the Lapland-Kola Orogen (LKO) has provided a natural laboratory for studying Paleoproterozoic orogenesis. Yet, its tectonic setting and the processes that led to heating in the Lapland Granulite Belt (LGB) remain debated (Cagnard et al. 2011). We present new whole-rock geochemistry, zircon U-Pb ages, and Lu-Hf isotope data from intrusions across three key LKO units: the Tanaelv Migmatite Belt (TMB), LGB, and Inari Arc, together with preliminary P-T estimates from LGB metasediments. Across all three units, the intrusions show characteristic arc-type geochemical signatures: Nb-Ta depletion with elevated large ion lithophile element concentrations, consistent with subduction-related magmatism. The intrusions formed between 1962 ± 6 Ma and 1916 ± 9 Ma, while the oldest metamorphic zircon yield an age of 1912 ± 3 Ma. Zircon Hf isotope data reveal contrasting melt sources: Inari and TMB intrusions yield median two-stage model ages of 2.7-2.2 and 3.4-2.3 Ga, indicating derivation from or interaction with Archean substrates, whereas LGB intrusions show no evidence of Archean input. Preliminary elastic thermobarometry (quartz-in-garnet) and Ti-in-biotite thermometry suggest relatively low-pressure, high-temperature peak conditions in the LGB, broadly consistent with <7 kbar and <900 °C. Trace element zoning in garnet distinguishes between initial solid-state prograde growth, subsequent melt-present growth with oscillatory phosphorus zonation, and final retrogression marked by almandine-rich rims together with the growth of biotite and cordierite. These results suggest that the LKO terranes represent arc systems assembled during the ca. 1920-1900 Ma Lapland-Kola Orogeny, with the LGB distinguished by limited crustal inheritance and high-temperature metamorphism.

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O17.18

Two-stage metamorphism in the Saimaa area, Southern Finland

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Understanding how high-temperature metamorphic terrains evolve is central to reconstructing the tectonic and thermal evolution of ancient orogens. Within the Paleoproterozoic Svecofennian orogen, the Saimaa area offers an exceptional field setting for examining these processes. The bedrock is dominated by pelitic metasedimentary rocks, which are well-suited for metamorphic modelling. The area also preserves a continuous succession of metamorphic zones from andalusite mica schists in the north to garnet-cordierite-K-feldspar-spinel migmatites in the south, offering a great opportunity to trace progressive metamorphism across a crustal section.

Korsman (1984) noticed that the progressive metamorphic zoning in the Saimaa area is not spatially related to magmatic intrusions, which would be expected if the high-temperature metamorphism was produced by magmatic heating of shallow crustal levels. Since then, several tectonic models have attempted to explain the development of the high temperature-low pressure metamorphism by crustal thinning, thickening induced heating or mafic underplating.

This study investigates whether the present-day metamorphic zoning in the Saimaa area can be explained by the superposition of two metamorphic cycles. Specifically, we assess how melt loss during an earlier event affects mineral assemblages, solidus position, and melt productivity during a later high-temperature overprint. Using thermodynamic modelling in rock-specific chemical systems, integrated with field observations, mineral chemistry, and bulk composition data, we propose a new two-stage metamorphic model for the Saimaa region.

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Identifying migmatite and leucogranite protoliths through thermodynamic forward modeling: a case study from Southern Finland

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When the continental crust melts in high-temperature metamorphism, the products of partial melting (leucosomes and leucogranites) are influenced by the composition of their protoliths and melting processes. The presence or absence of fluids during melting as well as the presence of possible peritectic phases also affects the composition and amount of melt. Thus, identifying the protoliths based on the melt products and the melt-depleted residues is sometimes difficult.

During the late stage of the Svecofennian orogeny, at c. 1.85–1.81 Ga, the thickened continental crust, which comprised a variety of metavolcanic and -sedimentary rocks interspersed with intrusive rocks, was subjected to widespread partial melting (e.g., Nironen 1997). In southern Finland, partial melts mainly formed through dehydration melting of metaigneous and metasedimentary rocks (Kuhila et al. 2010; Andersen & Rämö 2021), but for the very southernmost part – the Hanko peninsula and its surrounding archipelago – the protoliths for the local leucogranites and migmatites are not well constrained (Saukko et al. 2024). The metamorphic grade was higher and the compositions of the melt products are also distinct (e.g., notably enriched in K).

To identify possible protoliths for the Hanko migmatites and leucogranites, we ran thermodynamic models on plausible protolith compositions sourced from areas of lower metamorphic grade in southern Finland and compared the model results to samples from the study area. We also aimed to narrow down the melting conditions, such as the PT-ranges and effect of fluids. Our results indicate that the crustal melting event in southernmost Finland likely took place at around 4 kbar and 750–850 °C and affected broadly similar protoliths as elsewhere in southern Finland, but melting was water-present. The K enrichment is not reproduced by modeled melting alone, indicating some additional K input took place, possibly through metasomatism. In addition, different types of leucogranites in the area seem to be derived from different protoliths.

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O17.20

Zircon, monazite and xenotime geochronology on cordierite-orthoamphibole rocks in Orijärvi, southern Finland

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The Orijärvi region contains cordierite-orthoamphibole rocks (COR) that host VMS-type ore deposits. We have sampled two such CORs: one close to the closed Orijärvi mine and one from the Ilijärvi mineralized zone. U-Pb analyses on monazites, zircons and xenotimes were conducted on separated minerals and in-situ on thin sections by LA-SC-ICP-MS at the Finnish Geosciences Research Laboratory at the Geological Survey of Finland in Espoo.

The COR from the vicinity of the Orijärvi mine yielded zircons of various morphologies. These show three weighted average ²⁰⁷Pb/²⁰⁶Pb age populations of ~1.88 Ga, ~1.83 Ga and ~1.80 Ga. Monazites are also of various morphologies and yield a weighted average ²⁰⁷Pb/²⁰⁶Pb age of ~1.80 Ga. Xenotimes are rounded in shape and yield a weighted average ²⁰⁷Pb/²⁰⁶Pb age of 1.82 Ga. The Ilijärvi COR contained only few altered zircons which produced analyses with huge errors. The monazites are mostly rounded in shape, and the main population yield a weighted average ²⁰⁷Pb/²⁰⁶Pb age of ~1.83 Ga. Xenotimes are rounded and have a weighted average ²⁰⁷Pb/²⁰⁶Pb age of ~1.78 Ga.

The ~1.88 Ga age population of the Orijärvi COR zircons is similar to the established igneous age of the unaltered protolith (Väisänen & Mänttari 2002). The Orijärvi zircon age population of ~1.83 Ga and the xenotime ages of ~1.82 Ga are concurrent with the late-orogenic metamorphism in southern Finland. The Ilijärvi monazite ages of ~1.83 Ga also fit in this time bracket. Both samples also yield younger age populations. The age group of ~1.80 is present in the Orijärvi COR zircons and monazites. Such ages have been obtained earlier from the Orijärvi (Väisänen & Kirkland 2008). These ages are concurrent with post-collisional Svecofennian magmatism (Rutanen et al. 2011). The youngest age group recovered was the ~1.78 Ga from Ilijärvi xenotimes. In southern Finland, such ages have previously been reported from the vicinities of shear zones (e.g., Torvela et al. 2008). Orijärvi is bounded by two prominent shear zones: Jyly and Kisko which might have affected the Ilijärvi xenotimes.

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P17.1

Building the first continents: Archaean TTGs from the Lake Inari terrain, Arctic Fennoscandia

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How did Earth's first continents form and stabilize? A key step was the conversion of basaltic crust into buoyant, felsic tonalite–trondhjemite–granodiorite (TTG) crust during the Archaean (4.03–2.50 Ga). Partial melting of hydrated mafic rocks is widely regarded as the main mechanism, yet rarely tested against field evidence. Here we present new evidence from the 2.9–2.6 Ga Lake Inari TTG–metabasalt terrain in Arctic Fennoscandia, where field structures, migmatites and geochemistry capture the transformation in action. The Inari TTGs comprise two coeval geochemical endmembers—low-HREE and high-HREE—reflecting contrasting melting and magma interaction pathways. Their trace element signatures indicate multiple magmatic pathways controlled by variations in source mineralogy, degrees of partial melting, subsequent differentiation and magma mingling. Migmatite structures, from metatexites through diatexites, record processes of melt segregation, extraction, migration and redistribution (SEMR) under syn-anatectic deformation. The metabasalts occur as raft-like bodies interpreted as remnants of an overlying basaltic lid. Migmatite textures reveal progressive weakening of thickened basaltic crust and large-scale redistribution of melt under strain. Given that the metabasalts geochemically resemble Phanerozoic oceanic plateau basalts, we interpret this terrain as the deep, migmatized roots of a basaltic plateau above a mantle plume, operating in a stagnant- or sluggish-lid tectonic regime. These results provide rare, field-based confirmation that TTGs derived from plateau basalts were a driving force in the emergence of continents.

P17.2

Building Granitic Crust in the Southern Svecofennian: Rethinking Palaeoproterozoic Migmatite Genesis

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Analytical methods, progressively evolving toward smaller scales, offer new opportunities to improve our understanding of crustal evolution in high-grade terranes such as the Svecofennian orogeny (1.92-1.81 Ga). LP-HT metamorphism during the late-orogenic stage (c. 1.84-1.81 Ga) marks a period of extensive crustal anatexis, producing voluminous in situ, in source and injected leucosomes in southern Finland. Migmatites within this Late Svecofennian Granite-Migmatite Zone (LSGM) have traditionally been interpreted as the result of a single partial melting event 1.84-1.81 Ga. However, recent evidence suggests the occurrence of multiple metamorphic peaks, resulting in leucosomes with non-overlapping ages (Saukko et al. 2024). These findings remain tentative due to their reliance solely on zircon U-Pb data, which are often discordant and affected by common Pb in high-grade settings.

This project aims to address these gaps by applying a novel method: In situ isotope and trace element analysis of zircon-hosted inclusions using Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS)—so far unused in Finland—offers a way to circumvent the effects of high-grade metamorphism and obtain reliable geochemical and geochronological data. The data will provide new constraints on the sources, genesis and ages of leucosomes in the LSGM.

In our study, we will use apatite inclusions protected from post-crystallization alteration as a robust tool to investigate the early crystallization history of leucosomes. Compared to zircon, apatite is more sensitive to trace element (REE) fractionation, incorporates volatiles (F-Cl-OH and S) and is valuable source for Sr-Nd isotopes (e.g., Kendall-Langley et al. 2021; Moreira et al. 2023). We hypothesize that apatite inclusions shielded by zircon can preserve geochemical fingerprints not retained in zircon itself, helping us identify protoliths and source characteristics of leucosomes, assess the role of volatiles during anatexis, and help to determine whether melting was continuous or episodic.

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P17.3

Isotopic mapping of Sveconorwegian crust: Implications for nickel mineralisations in southern Norway

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The Sveconorwegian Province of SW Fennoscandia, covering much of southern Norway, comprises a mosaic of lithotectonic units assembled during the Sveconorwegian orogeny (c. 1.2–0.9 Ga). Traditionally, these units have been distinguished by distinct geological features, reflecting the protracted evolution of an active continental margin (c. 1.8–1.4 Ga). However, recent syntheses of geological data, including refined chronological and isotopic analyses, suggest that unit boundaries should be reevaluated in some areas (Orvik et al. 2025). A key example is the Kongsberg Unit, east of the Oslo Graben, where mafic magmatism can be subdivided into three sub-units based on age and isotopic signatures. The oldest and Ni-prospective phase (c. 1.61–1.52 Ga) occurs in the northern Kongsberg Unit and extends into the Idefjorden Unit. Comparable mafic magmatism is recorded southeast of the Oslo Graben (e.g. 1.55 Ga Romsås deposit; Mansur et al. 2023), indicating coeval processes that cross traditional unit boundaries. The distribution of Ni deposits also correlates with regional Hf isotopic gradients, particularly a marked east–west decrease in Hf model ages (Orvik et al. 2025). Similar relationships have been recognised in the Yilgarn Craton, Western Australia, where isotopic datasets support models linking lithospheric architecture to orthomagmatic Ni mineralisation (Mole et al. 2015). However, in the Sveconorwegian context, sparse isotopic data still limit the resolution and confidence of such regional interpretations. To address this, we present a new, extensive zircon U–Pb–Hf isotope dataset from the Bamble and Idefjorden Units. These data significantly improve coverage of Ni-prospective terranes and offer new constraints on the timing and geodynamic context of mafic magmatism. Our findings refine the isotopic architecture of the Sveconorwegian crust and provide critical input for next-generation exploration models across SW Fennoscandia.

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P17.4

Three-dimensional resistivity model of Bothnian region reveals geometry of large-scale geological units

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The Bothnian region of western Finland represents a key area for understanding Precambrian crustal evolution, where Archean complexes collided with supracrustal belts and oceanic arc lithologies during the Svecofennian orogeny. Yet, the deep architecture of this region remains uncertain. Broadband magnetotelluric (MT) imaging provides an opportunity to probe the entire crust, given its excellent penetration depth especially in highly resistive cratonic environments. Previous MT surveys in the region have largely been limited to 2D profiles (e.g., Korja et al. 1986; Chopin et al. 2020) and have supported interpretations such as those of Chopin et al. (2020), who proposed that metamorphic suites extend beneath the Central Finland Granitoid Complex (CFGC). However, such interpretations remain uncertain without modern 3D resistivity constraints.

To address this gap, Harjulehto (2025) combined legacy MT data with new measurements to construct a 3D resistivity model of the Bothnian region. The resulting model reveals a previously unknown distinct conductor beneath the CFGC that does not appear to connect with the adjacent Pirttikylä or Lappfors metamorphic suites. Furthermore, the model highlights new perspectives on other large-scale tectonic features, including the Keitele and Bothnian microcontinents and the Fennoscandian large-scale conductor (Engels et al. 2002), which crosses the study area. Although Harjulehto's model identifies a clear anomaly associated with this conductor, its continuation remains unresolved.

The motivation of the ongoing work is to verify and refine the spatial distribution of major conductors and resistors in the region, and to test tectonic hypotheses regarding crustal discontinuities and the interaction of major geological units. To achieve this, additional ~ 10 broadband MT soundings will be collected in autumn 2025 over the most interesting areas. These new data, combined with targeted numerical modeling, will allow a critical assessment of the relationship between the CFGC, the metamorphic suites, and the deep conductors, thereby advancing understanding of crustal evolution in the Fennoscandian Shield.

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P17.5

Initial Look at the Wiborg Rapakivi Granite Batholith from the First Seismic-Reflection Survey in the Kymenlaakso Area, Southern Finland

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The Wiborg rapakivi batholith (WRB; 1.65–1.62 Ga) covers much of southeastern Finland and is considered relatively homogeneous, lacking obvious tectonic or intrusive structures. The WRB has recently attracted interest as a potential geothermal resource due to its high radiogenic heat production and favourable thermal conductivity. To evaluate the feasibility of using the rapakivi granites for geothermal heat production and to better constrain the batholith's internal structure and depth extent, GTK acquired new surface geophysical data in 2024 within the Geoenergy Leap project—gravity, magnetotelluric (MT) data, and 2D seismic reflection profiles—in the Kymenlaakso region (projektit.gtk.fi/geoenergialoikka).

Previous seismic studies from the area include crustal-scale wide-angle refraction/reflection experiments (BALTIC, SOFIC). Their velocity models, together with regional seismicity and thermal constraints, indicate that the WRB is an upper-crustal, relatively low-V_p body that crops out and is likely confined to roughly the upper ~0–10 km; however, these data do not provide detailed near-surface information or the internal structure of the WRB.

The 2024 Kymenlaakso2D seismic reflection survey is, to our knowledge, the first dedicated high-resolution survey in the region, providing more detailed imaging of the batholith and surrounding structures. Three profiles (~42 km total) were acquired: two N–S (~24.7 km and ~10 km) and one W–E (~7 km) intersecting the longest N–S line in the southern part. Acquisition used a mix of sources: mainly a 32-ton vibroseis truck (50 m shot spacing) and limited explosives (100 m spacing, northernmost line only). The FINSIP instrument pool provided ~900 3C nodal receivers with 5-Hz geophones (Geospace GSB) deployed at 25 m receiver spacing and rolled along the profiles.

The dataset, high quality for hard-rock conditions, images reflectors across much of the profiles. Seismic sections show weak, spotty reflectivity in the upper few kilometers, consistent with relatively homogeneous granite beneath thin Quaternary cover, with a few stronger near-surface events. A laterally coherent package at ~8–10 km depth (most evident on the northernmost line and partly on the southern line) most likely marks the basal contact of the WRB, which is consistent with previous studies. Beneath this depth range, a deeper reflective band suggests lower-crustal layering. Localized breaks in reflector continuity observed throughout the sections may indicate fault or fracture zones.

The new seismic survey delivers a more detailed view of the WRB and its surroundings, paving the way for in-depth, integrated interpretation and a re-evaluation of the batholith's internal structure, depth extent, and geothermal potential.

P17.6

Age and character of granophyric and composite dykes in Kiirunavaara, northernmost Sweden

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Two sets of magmatic dykes cut the Kiirunavaara iron oxide-apatite ore body at high angle: 1) a set of 0.1-20 m wide felsic dykes, striking NW, steeply dipping to the NE, in the south, and 2) two composite mafic-felsic, 2-15 m wide dykes, striking W-NW and dipping 60-70° S-SW, in the north. The felsic rocks typically show granophyric textures. The composite dykes as a rule have mafic margins and felsic interiors, with bulbous contacts and mafic enclaves in the felsic centres, implying co-mingling of mafic and felsic magmas. Apophyses of both mafic and felsic composition are noted. A granite pluton that contains mafic enclaves occurs in the footwall rocks of the orebody, adjacent to the dyke systems.

One sample of felsic rock from each dyke system was sampled for SIMS U-Pb zircon geochronology. Zircon from the composite dyke are weakly oscillatory zoned, partly metamict, and subhedral giving a concordia age of 1879 ± 6 Ma (MSWD=0.8; n=14). A weighted average $^{207}\text{Pb}/^{206}\text{Pb}$ age yielded 1881 ± 6 Ma (MSWD=1.2; n=14). Zircon in the southern dyke was high in U, typically 1500-2500 ppm, and with small fluid inclusions, ≤ 1 mm across, contributing to a high common Pb content, resulting in highly discordant data. Thirty-two analyses define a discordia with upper and lower intercepts at 1872 ± 14 Ma and 423 ± 14 Ma, respectively, and a MSWD of 28. One analysis was concordant at 1861 ± 10 Ma.

The strong metasomatism affecting most of the volcanic country rocks (cf. Pihl 2024) has also altered many of these dyke rocks. However, most of the rocks of this study fall within the fields of igneous or least altered whole rock compositions. Classifications indicate that the mafic rocks are continental arc type, with some E-MORB influence. Both the granite and the granophyres are high-silica types ($>70\%$ SiO_2), but the granophyres more elevated ($>75\%$). The granite shows continental arc signature, while the granophyres are transitional into the within-plate fields.

We interpret the results to indicate that mafic and felsic magmas intruded shortly after ore emplacement, penecontemporaneous with the granite and in a continental arc setting. The within-plate character of the felsic dykes may be the result of crystal fractionation rather than a separate magmatic event. A significant part of the metasomatism occurred syn- to post-dyke magmatism, corroborating previously reported later episodes of hydrothermal activity in the area (e.g., Yan et al. 2023).

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P17.7

Reconstructing craton evolution in Finnish Fennoscandia using radiation-damaged zircons, low-temperature thermochronology, and numerical models

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Cratons are areas of stable, ancient lithosphere that comprise the interior of many continents. In Fennoscandia, geological evidence suggests the Fennoscandian Shield may be among the most stable, slowly eroding regions on Earth over the last 1.5 Ga (Hall et al. 2021). However, low-temperature thermochronology data suggests this same region may have experienced numerous episodes of kilometer-scale burial and exhumation in the last 1.1 Ga (Green et al. 2022). This raises a natural question: How stable is the Fennoscandian Shield?

We address this question using (U-Th)/He low-temperature thermochronology and numerical modeling. (U-Th)/He thermochronology is based on the temperature-dependent retention of radiogenic He produced by the decay of U and Th in minerals such as apatite and zircon. While temperature strongly affects He diffusivity in crystals, decay itself creates damage zones that can alter the temperature ranges of He retention (e.g., from ~200 to 0 °C in zircon) and produce age dispersion within a sample due to varying parent isotope concentrations. Here, we take advantage of the age dispersion to reconstruct detailed cooling histories of 19 rock samples from across Finland. These new data are interpreted using the thermochronology software package Tc1D (<https://github.com/HUGG/Tc1D>), which has recently been extended to support inverse modeling of thermochronometer ages using several Bayesian approaches.

Preliminary results from 62 new single-grain zircon (U-Th)/He dates range from ~1500 to ~2 Ma with substantial date variation both within samples and across the study area. Regions proximal to the Caledonian front generally have younger dates of <400 Ma, suggestive of cooling following burial and exhumation after Caledonian orogenesis. In central and southern Finland, dates are older but exhibit a strong dependence on the amount of accumulated radiation damage approximated by the parent isotope concentrations. The decrease in date with increasing parent isotope concentration is suggestive of stability and very slow exhumation over the last ~1.5 Ga.

Ongoing work focuses on integrating 55 new apatite (U-Th)/He dates from the study samples, an additional 25 zircon (U-Th)/He dates from the Kola peninsula, and low-temperature thermochronology data from past studies into a common dataset. This data will be explored via inverse models using the Tc1D software to determine the timing, magnitude, and rates of burial and exhumation they record. These dates and rates will provide insight into processes affecting craton stability.

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P17.8

Preliminary character and geochronology of a spinel-olivine-phlogopite rock, central Sweden: a piece of metasomatized upper mantle/lower crustal cumulate, or something else?

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A conspicuous blueish rock was found in material from a tunnel excavation at Bäckesjön, south of Hennan, Hälsingland, Sweden, in a moderate to high-T, low P metamorphic domain of the Ljusdal lithotectonic domain. The main minerals are: spinel, olivine, and phlogopite, suggesting the name olivine-phlogopite spinellite. Accessory phases are, e.g., zircon (abundant; in places with intergrowths of baddeleyite), calcite, and hematite, and secondary serpentine (after olivine). The composition of spinel and olivine (forsterite) approach the nominal endmembers: $\text{Mg}_{0.90}\text{Fe}_{0.10}\text{Al}_{1.98}\text{Fe}^{3+}_{0.03}\text{O}_4$ and $\text{Mg}_{1.90}\text{Fe}_{0.11}\text{Si}_{0.99}\text{O}_4$, respectively.

Phlogopite is Mg-rich with a significant eastonite-component

$\text{K}_{0.99}\text{Mg}_{2.69}\text{Al}_{0.21}\text{Fe}_{0.1}\text{Al}_{0.99}\text{Ti}_{0.01}(\text{Si}_{2.79}\text{Al}_{0.21})\text{O}_{10}(\text{OH})_2$. The texture is coarse-grained with grains up to c. 10 mm in size, particularly spinel. Phlogopite has partially replaced forsterite. Calcite and hematite occur in fracture fillings in both olivine and spinel. The rock is surrounded by a gradational apparent reaction zone composed predominantly of biotite.

Zircon occur as well rounded clear crystals devoid of cracks and inclusions. SIMS U-Pb zircon analyses (n=22, all concordant) define a concordia age of 1858 ± 3 Ma (MSWD=1), suggesting U-Pb isotopic homogeneity. The age of the oscillatory zoned zircon is interpreted to date igneous crystallisation of the protolith and it is within the range for igneous crystallization ages of the surrounding granitoids of the Ljusdal batholith (and associated mafic rocks; Högdahl & Bergman 2020). Regional metamorphism in the upper amphibolite to granulite facies have affected rocks in the region shortly after magmatism and later at 1830–1800 Ma (Högdahl & Bergman 2020).

Similar rocks have been interpreted as strongly metasomatized upper mantle peridotites or dunitic cumulates (e.g., Rajesh et al. 2004). However, the aluminous character may call for a more Al-rich protolith, e.g., a plagioclase-rich (troctolitic) cumulate, where all feldspar has reacted out. The surrounding rock type is not exposed, but the biotite margin may represent a reaction zone with the enclosing magma during transport within the crust or by later regional metamorphism. An origin by high-temperature recrystallization of a strongly Al-Mg-enriched supracrustal rock cannot, however, be excluded. To our knowledge, this is the first reported rock of this kind in Sweden.

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O18.1

Earliest hominin environments in Western Europe? – palaeoenvironmental reconstructions of Early Pleistocene Orce sites in Andalucia, Spain, based on fossil mammal communities

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Some of the earliest evidence of the presence of early humans (*Homo* sp.) in Western Europe comes from the localities of Barranco León and Fuente Nueva 3 near the village of Orce in Southern Spain, ca. 1.4 and 1.2 million years in age, respectively. Furthermore, the environmental conditions in these sites can be compared with the slightly older, ca. 1.6 Ma locality of Venta Micena, which represents the conditions before the arrival of humans. We used the distribution of dental functional traits and mean body mass estimates within fossil large herbivorous mammal communities to estimate climate (mean annual temperature and mean annual precipitation) and primary production in the Orce palaeoenvironments, and compared these with a broad range of Early Pleistocene sites from Europe and especially the Guadix-Baza Basin where the Orce sites are located. We showed that humans arrived in the Guadix-Baza Basin under warm and relatively humid climate, when primary production was relatively high, especially compared with Venta Micena, which represents time just before human arrival in the basin. Furthermore, dietary analyses based on mesowear (macroscopic worn shape of molar tooth surfaces) of large herbivorous mammals indicate prevalence of browsing rather than grazing species, suggesting scarcity of grassy vegetation in the early human sites of Orce compared with the more open, climatically harsher and more grass-dominated Venta Micena. The dental trait distribution and mesowear analyses indicate the presence of Mediterranean woodland environments which were notably different from the East African tropical savanna environments where the early humans originated, suggesting notable ecological flexibility of early humans. Relative abundances of large mammal taxa offer a further possibility to explore the variation of environmental conditions within the sedimentary sequences from Barranco León and Fuente Nueva 3. The mammal ecometrics - based palaeoenvironmental estimates correspond with similar results from climatic tolerance ranges of small vertebrates and fossil pollen assemblages from the Orce sites.

O18.2

Palaeoenvironments of hominins in Central Asia – insights from loess-palaeosol deposits

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Ancient hominins repeatedly occupied Central Asia over the past ~800 ka, as evidenced by lithic tools preserved in the loess deposits of the Khovaling Loess Plateau in southern Tajikistan. However, the richest assemblage of lithic tools found in the region, the Karatau Culture, is found only in palaeosols associated with Marine Isotope Stages (MIS) 11, 13, and 15, with intervening glacial periods as well as previous and subsequent interglacial periods characterised by a near absence of tools. Currently, the cause of these alternating phases of occupation, as well as the reasons for the emergence and demise of the culture remain unclear.

As well as preserving the lithic artefacts associated with the Karatau culture, the Khovaling Loess Plateau loess-palaeosol sequences provide an opportunity to understand the climatic and environmental context of the culture's appearance and disappearance. Indeed, the Khovaling Loess Plateau is located in a transitional zone between climate systems (Mid-Latitude Westerlies, Siberian High and Indian Monsoon) and may be particularly susceptible to global climate reorganisations within the Quaternary. In this study, we apply magnetic techniques (multi-frequency magnetic susceptibility and anisotropy of magnetic susceptibility, AMS) to the Khonako-II loess-palaeosol sequence of the Khovaling Loess Plateau to investigate dust transport dynamics and variations in the intensity of hydroclimate during the emergence, presence, and disappearance of the Karatau Culture in southern Tajikistan. In this way we test the possible link between changing environment and human occupation in the region.

Our AMS results indicate stable regional dust-transporting winds over the past ~1.2 Ma, including the occupation periods of the Karatau Culture. In contrast, variations in pedogenic magnetic susceptibility, calibrated against a modern-analogue based climofunction, reveal shifts in hydroclimate intensity. We demonstrate that glacial periods were indeed much drier, with amounts of annual precipitation reduced by nearly half compared to interglacial periods. Interestingly, the demise of the Karatau Culture coincides with a near-doubling of interglacial annual precipitation, suggesting that hydroclimatic shifts may have affected hominin occupation patterns in southern Tajikistan.

O18.3

Non-analogous faunal communities as proxies of environmental conditions in Nihewan basin (Northern China) during the Pleistocene

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The Nihewan basin is a rich and diverse Early Pleistocene fossil site in Northern China, which is suggested to be an ancestral site for the subsequent faunal communities in central Asia (e.g., Mammoth steppe fauna). The Nihewan basin is also associated with the earliest Palaeolithic remains in Eastern Asia, which makes it a unique site to study environmental conditions that early humans were existing in.

Our approach is to analyse ecomorphological species composition of the Nihewan Pleistocene faunas by identifying the most representative species and genera of the cold versus warm and dry versus moist conditions throughout the Pleistocene (e.g., Caprini (wild goats and sheep) and Suidae (wild pigs)).

O18.4

Pleistocene Niche Evolution of Humans in East Asia

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Modern humans are capable of adapting to a wide range of environments, occupying nearly all biomes on Earth and becoming a dominant force in shaping ecosystems. However, it remains unclear when this broad ecological flexibility first emerged during humans' history.

Using the Pleistocene mammalian fossil record from China, we investigate how the ecological niche of humans evolved and how this process affected another large primate in the region – *Gigantopithecus blacki*. We apply two independent approaches—dental ecometrics and climate model simulations—to reconstruct past precipitation and temperature conditions at Pleistocene mammal fossil sites, where we have information about the presence of humans and *Gigantopithecus blacki*. We further developed a biome prediction model based on dental traits, that allows us to infer the paleobiomes for human and *Gigantopithecus* sites. We use these sources of information to track changes across Pleistocene in the range of suitable conditions and the size of ecological niche of humans and *Gigantopithecus*.

Our results show that *Homo erectus* in East Asia already occupied multiple environments, although the core of the human niche was centered in a relatively narrow open-forest biome. Many archaeological sites without human fossil remains were reconstructed as dry shrubland/steppe environments, which we interpret as representing marginal habitats for *H. erectus*, likely occupied only seasonally. In contrast, no evidence of humans is found in the dense forests in southeastern China, which were instead inhabited by *Gigantopithecus blacki*. From the Late Middle Pleistocene onward, human core niche expanded significantly, extending into both dense forests to the south and shrubland/steppe to the northwest. This niche expansion may reflect the presence of multiple human lineages occupying different niches, or the appearance of taxa such as Denisovans (or *Homo longi*) with broader ecological niche. By contrast, *G. blacki* underwent a marked contraction of its niche toward southern China, ultimately resulting in its extinction. During the Late Pleistocene, the human niche broadened further, with *Homo sapiens* occupying nearly all available terrestrial biomes.

O18.5

Did dog domestication initiate the Anthropocene?

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Humans are unique in many ways. However, many characters once considered specific to humanity have now been questioned as traits such as transfer of culture and toolmaking are documented for many other animals as well.

Domestication of animals and plants maybe one of the few behaviors that remain unique to humanity. Domestication has secured food sources and enhanced long distance traveling. It most likely was a key for human dominion, and lead to the Anthropocene (e.g. Young 2016).

Dogs were the first domesticates. They were domesticated from wolves by paleolithic hunter-gathers. We have argued that the dog domestication was enabled by physiological constrains in humans (Lahtinen et al. 2021).

When the hunter-gathers became a part of the large carnivore guild, the competition within sympatric large carnivores was restricted by different dietary requirements (Speth 2024). Here, using the fossil and written record, we find evidence that the human perception of large carnivores as competitors is probably a very recent phenomenon, and the domestication of dog did not result in attempts to extirpate the wolf.

We suggest that although according to the early Anthropocene model the heavy human impact on nature started with the neolithic revolution, domestication as such may not have been a starting point for the Anthropocene.

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O18.6

Tracing anthropogenic impact since the Bronze Age in partly varved lake sediments from Tiefer See, southern Baltic lowlands

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Varved lake sediments are high-resolution archives for climate and environmental change. Due to their location in the human habitat, lakes also record human activities since prehistorical times until the most recent impacts related to industrialisation and intensive agriculture. It is challenging to distinguish between human and climatic influences but novel proxies including biomarkers and sedimentary DNA provide tools for tracing anthropogenic impacts in lake sediments. Here, we present a case study from the partly varved sediment record of Lake Tiefer See, located in the formerly glaciated landscape of southern Baltic lowlands. The lake basin formed in a subglacial valley and lacustrine sedimentation commenced ca 13,000 years ago. The lake is situated in a region dominated by agriculture but presently is surrounded by a narrow belt of trees separating the lake from surrounding fields. The 62 m deep lake has no direct major inflow and the sedimentation is largely controlled by lake-internal processes with only minor detrital material from the catchment. Presently, the lake forms varves since about a century. Tiefer See is part of a long-term monitoring programme (Brauer et al. 2022) and sediment trap studies revealed a full understanding of seasonal sedimentation processes forming calcite varves (Roeser et al. 2021). The intercalation of varved and non-varved intervals throughout the Holocene has been discussed by Dräger et al. (2017). In this study we combine pollen as indicators for landscape openness with stable ¹⁵N analyses of organic matter and different biomarker proxies for human activities and compare initial evidence of human impact in the catchment and the lake during the Bronze Age with the strong influences of humans in recent times. We discuss the findings from Tiefer See in the context of the global concept of the Anthropocene.

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O18.7

Microplastics in Icelandic Lake Sediments: Lessons and Findings from a Multi-Tool Approach

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Microplastics (MPs) are a persistent pollutant that will likely remain in the environment for millennia, adding to the list of long-lasting anthropogenic markers present in natural archives. While depositional environments such as lakes can be effective at retaining airborne pollutants, they are very much understudied when it comes to MP pollution, especially in Arctic and sub-Arctic regions. However, in such extreme conditions as in polar settings, investigating lake-sediment records can prove to be a relatively accessible, reliable, and cost-effective method to study the deposition of MPs.

Over the past few years, we used a multi-tool approach to assess the potential of Icelandic lake sediments to be used as a medium for MP pollution studies, therefore evaluating the scale of human impact in a remote sub-Arctic context. Specifically, we used a combination of sediment traps and short sediment cores to quantify MP deposition fluxes in different lake settings across Iceland. In total, ten lakes were investigated, including the largest natural lake in Iceland, Þingvallavatn, crater lakes such as Bárðarlaug, as well as urban lakes and remote catchments. For easily accessible lakes, we deployed sediment traps that were retrieved every six months, whilst surface sediments from remote and hard-to-access lakes were collected using a short corer. MPs were extracted from sediment samples using a heavy liquid separation method, followed by organic matter elimination with an enzymatic purification protocol, and identified using micro-FTIR spectroscopy analyses.

Out of the ten selected targets, all of them were found to contain MPs, with flux values ranging from 1.2 particles/m²/day in an unnamed lake located on Langanes, (remote peninsula in northeast Iceland), to 1294 particles/m²/day in Meðalfellsvatn, (urbanized lake surrounded by summer cottages in the capital region). Across all lakes, polymer types such as polypropylene (PP) and polyethylene (PE) dominated over other polymer types. These results emphasize the ubiquity and persistence of microplastic contamination, highlighting how even regions far from major population centres have a distinct anthropogenic signature. Furthermore, our results highlight that MP accumulation in lake sediments can vary significantly, and that it is likely driven by a complex interaction between precipitation, wind patterns, and local topography.

O18.8

Trap the Change: How Ferry Traffic Impacts Coastal Ecosystems

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Coastal areas experience intense maritime activity, including frequent ferry traffic. The wakes of large vessels disturb the nearshore zone and alter coastal processes, inducing sediment resuspension and destabilisation of littoral ecosystems (Erm et al. 2009). Furthermore, ship-induced physical disturbance of the coastal sediments enhances coastal methane emissions, which significantly contribute to global warming (Nylund et al. 2025). According to the recently published review on marine biodiversity loss, the physical disturbance of the seabed is one of the most common causes of biodiversity loss in Finnish coastal waters (Sumelius et al. 2025). In this research, a prototype of an innovative online sediment trap is utilised to capture evidence of nearshore disturbance induced by the Turku-Stockholm ferry lane in the Archipelago Sea, Finland. The research aims to quantify sediment disturbance and assess the rate of ecological impacts resulting from frequent ferry traffic. The online sediment trap is a prominent Finnish invention that is equipped with a computer tomography function (Johansson et al. 2019). This feature enables the direct quantification of sediment disturbance rates of ferry traffic at an hourly timescale. The collected high-resolution monitoring data is analysed using statistical and machine-learning methods to uncover the hidden patterns and drivers within the data. These insights will then be interpreted in the context of sedimentological processes in the coastal environment to support sustainable maritime management and protection of the fragile shallow and coastal environments of the Archipelago Sea.

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O18.9

Art and the Mediation of Scale in the Anthropocene

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Since its origins in the natural sciences, the Anthropocene concept has expanded into a wider range of disciplines through a reframing spurred by a *geologic turn* in the social sciences, humanities, and arts (Palsson & Swanson 2016). The resulting discussion has fostered geologic practices and thinking that extend beyond the Earth sciences, transforming the original geologic concept into a critical framework and cultural phenomenon (Berger 2020). The scales we deploy to orient ourselves in the world are not entirely given through physical conditions but also a continuous product of historical, sociocultural, and technological processes (Hecht 2018). The Anthropocene challenges humanity's understanding of human-relevant scales. For example, climate breakdown can only be addressed with an understanding of the planetary scale and with a time horizon that spans many generations. We find ourselves in a situation where current scalar thinking is not able to respond to the new scalar realities brought about by human activity. My paper frames the Anthropocene as a crisis of scale (Clark 2012), demonstrating a disjuncture between contemporary life and the planetary rhythms that form the foundational conditions of human existence (Irvine 2020). I argue that fully understanding this disconnect requires a re-examination of scale across temporal, spatial, and material dimensions throughout different disciplines. As art can be considered a system for the reproduction and renewal of societies and culture (Gell 1998), this presentation considers how artistic practices can contribute to the process of re-examination of scale. To this extent, this paper discusses artistic practices not as passive reflections of an Anthropocene condition, but as active cultural techniques that materialise, mediate, and critique scale. The paper will introduce a selection of artworks and exhibitions that explore questions of the Anthropocene and scale, and with it, asks how art can contribute together with science to find humanity's place in deep time.

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P18.1

Rapid Development of Hypolimnetic Hypoxia and Varve Formation in an Urban Finnish Lake Enhanced by Anthropogenic Actions

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Anthropogenic actions can significantly influence the environmental conditions of urban water bodies. Maljalahti Bay, located adjacent to the city of Kuopio at the northern end of Lake Kallavesi, has undergone many well-documented changes related to urban development over the past centuries. In this study, we investigated the influence of these activities on water quality and sediment characteristics at Maljalahti Bay through analyzing the physical and geochemical properties as well as the diatom assemblages contained within the sediment record. The sediment core was dated using varve counts in conjunction with the vertical distributions of ¹³⁷Cs and ²¹⁰Pb. The 1.6 m long sediment core has 95 varves between 0 and 92 cm depth. An 8 cm thick clastic layer observed at a sediment depth of 92–100 cm is likely associated with the bay filling event of 1913; a higher assemblage of *Aulacoseira islandica* in this depth is indicative of turbulent water. The older sediment deposited beneath this event layer lacks a distinct varve structure. This event, coupled with the initiation of sewage discharge into the bay in 1907, likely contributed to the development of hypolimnetic hypoxia and the subsequent formation of a weak varve structure from the 1920s onward. Following the construction of a breakwater in 1978, more distinct varves began to emerge in the sediment record starting in the 1980s. The excellent preservation of these varves indicates either rapid sedimentation or the presence of oxygen-depleted conditions at the bottom of the water column. Furthermore, the diatom assemblage data suggest that the Maljalahti Bay experienced gradual eutrophication with the discharge of wastewater to the bay and the establishment of the wastewater treatment plant in 1974 led to a reduction in the nutrient load entering the bay.

P18.2

Nihewan paleolake evolution and sediment provenance revealed by end-member modelling of size-shape distributions

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Human evolution is closely linked to climatic and environmental changes. Understanding which environments favored early human migration into new regions is crucial for tracing this evolution. Nihewan, in the northeastern part of the Chinese Loess Plateau, is globally recognized for its Early Pleistocene (c. 2.5–1.7 Ma) mammal fossils. Over the past century, the area has yielded a rich faunal record alongside more than 60 Paleolithic sites, with thousands of Oldowan-style stone tools found in situ. This makes Nihewan a key region for studying early human activity outside Africa.

The Nihewan Basin preserves a continuous terrestrial sequence from the Pliocene through the Pleistocene and into the Holocene. Pleistocene strata vary by depositional environment: mammal fossils are mainly found in river, floodplain, and fluvial fan deposits, while stone tools are typically associated with lakeshore sediments. Loess deposition in the area has persisted throughout the Quaternary, partially masked by other deposits. Despite decades of research, depositional context of the fossil localities and archaeological sites remains unresolved.

This study applies dynamic image analysis (DIA) to sediments from the Shanshenmiaozui mammalian fossil site, located 200 meters from, and stratigraphically correlated with, the Xiaochangliang archaeological site. DIA captures both grain-size and shape in fine-grained sediments. Combined with endmember modeling of size-shape distributions (EMM-SSD), this approach enables quantitative reconstruction of sediment sources, transport processes, and depositional environments – offering new insight into the environmental context of early human presence in Nihewan. Research is ongoing.

P18.3

Mixing regime shift in Lake Lyhyenjärvi

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Lyhyenjärvi (59.7 ha) is a calcareous, humic, eutrophic headwater lake with a poor ecological status, heavily impacted by agricultural runoff, wastewater from scattered settlements, and internal nutrient loading. Despite its relatively small catchment (18.1 km²), intensive land use drives disproportionate nutrient enrichment.

To investigate the lake's long-term response to environmental change, a 217 cm sediment core covering ~2000 years was analyzed. The sediment is partly varved, though the varve structure is intermittently disrupted, suggesting shifts in circulation and mixing regimes. Diatom assemblages indicate that Lyhyenjärvi has remained consistently eutrophic, yet a pronounced taxonomic shift from small *Pseudofragilaria* species to heavily silicified *Aulacoseira* taxa was observed. This transition points to changes in water column dynamics, with *Aulacoseira* dominance reflecting enhanced turbulence and altered stratification.

The results highlight the combined role of climate variability and anthropogenic stressors in reshaping lake circulation, nutrient cycling, and silica dynamics. Lyhyenjärvi thus provides a valuable case study for understanding how northern lakes may undergo fundamental regime shifts in their mixing processes under ongoing global climate change.

P18.4

Seasonal succession of diatoms in the coastal Baltic Sea: insights for their use as a micropaleontological proxy for past environmental change

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Diatoms are globally significant primary producers that play a key role in the carbon cycle, serve as sediment tracers in paleoceanography, and as bioindicators in environmental monitoring. Diatoms are excellent indicators due to their often species-specific, narrow environmental tolerances. However, the annual succession of diatom communities remains deficiently known, even in the relatively well-studied Baltic Sea, which limits their potential to reconstruct past seasonal changes in marine systems. Particularly, sedimentation processes beneath sea ice and during the ice-out are under-researched due to challenging late winter and early spring field conditions. Automated sequencing sediment traps offer an effective solution to this challenge, even during the ice-cover period.

In this PhD project, the seasonal succession coastal diatom communities and their contribution to vertical particulate organic matter fluxes and sedimentation are studied in Tvärminne Storfjärden, Gulf of Finland. The aim is to enhance our understanding of the seasonal patterns of diatom species succession and sedimentation at a high temporal resolution, with a focus on understanding future seasonal environmental drivers and the development of paleoenvironmental reconstruction methods. Data is collected with automated sequencing sediment traps, moored to the sea floor to continuously collect vertical material fluxes settling down from the sea surface at two-week temporal resolution. Two sediment traps are deployed at different depths to assess how processes like decomposition and predation impact the vertical sediment flux. One trap is deployed at 15 m depth and another at 27 m, approximately 3 m above seabed. The sediment trap data is compared to simultaneous environmental measurements of e.g., sea surface temperature, salinity and sea ice cover. Environmental measurements are conducted by the Tvärminne Zoological Station as a part of long-term environmental monitoring. Enhanced seasonal ecological information will improve diatom-based methods, enabling more accurate reconstructions of past and predictions of future coastal environments. The advancement provides valuable insights into the impacts of ongoing environmental change and anthropogenic pressure on aquatic systems and, ultimately human well-being.

P18.5

Hydrodynamic modelling of estuary flow characteristics for microplastic flux research

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The rise in plastic production has led to the accumulation of microplastics, defined as plastic particles smaller than 5 mm, in the environment. Evidence indicates that microplastic accumulation poses ecological risks, yet conducting accurate environmental risk assessments remains challenging. Microplastics are transported within aquatic environments in conjunction with other suspended solids, primarily organic and minerogenic materials. We used hydrodynamic modeling in the Baltic Sea Halikonlahti estuary, Southern Finland, aimed at clarifying the relationships between microplastics and various fractions of suspended solids during transport, accumulation, and resuspension.

The study area is a low-salinity, enclosed, and shallow estuary, where open water season flow characteristics are influenced by the discharge from two adjacent rivers and varying wind conditions. The model simulation, conducted from May 21 to October 10, 2018, is validated using continuous flow velocity measurements from one boundary of the modeling area. The results enable further modeling of sediment transport, accumulation, and resuspension. To improve model inputs and validate outcomes, surface bulk sediments, varved sediment, and sediment trap samples are analyzed.

The hydrodynamic modeling results categorize the estuarine bathymetry into regions exhibiting differing flow velocities, which can be used to guide sediment sampling in future research phases. Additionally, the predicted flow conditions indicate potential areas for microplastic accumulation and resuspension within the marine sediments of the estuary.

P18.6

Late Pleistocene Megafauna Extinctions - Timing and Causes

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Megafauna extinctions of the Late Pleistocene remain contentious despite decades of substantial research interest. The three predominant explanations are climatic change, human impact, or a combination of both. Here, I address the issue by combining a systematic literature review with a regional analysis of North American extinctions using Optimal Linear Estimation (OLE) modeling. Widely used in conservation biology, OLE has recently gained footing in paleontology and archaeology, offering a way to extend likely last appearance datums (LADs) beyond limits imposed by the Signor–Lipps effect. Using OLE-derived LADs with paleoclimatic and archeological proxies to estimate extinction chronologies, I assess the likely causes of North American extinctions and the methodological value of OLE in paleontological research.

Data gathered in the literature analysis is used to quantify the current state of the Late Quaternary extinction debate. Bias caused by the data used, the taxa included in the research, and research group perspectives is considered. A meta-analysis of the studies provides likely ages and causes of extinctions on different continents. The dataset of the study reveals a striking standoff between the three primary schools of thought, with climate, human, and mixed cause explanations each failing to gain a decisive lead, highlighting the ongoing debate within the field. The spatial scale of a study significantly affects its outcome, with global-scale studies most often pointing to human impact, whereas regional-scale studies more often attribute climate as the primary reason.

My results show that the OLE method is best suited for use with larger datasets ($n > 10$), as sparse fossil datasets can produce wide and potentially misleading confidence intervals. The narrowest confidence intervals were achieved when $n > 40$, although the temporal distribution of fossil data also strongly influences model outputs. As such, extinction estimates are shaped by research history and sampling bias. Although the Younger Dryas is considered an important climatic factor, extinctions occurred both before and after this period, with cold-adapted species surviving into the Holocene. Similarly, extinctions took place both before and after the emergence of the Clovis culture. Rather than a simple cause-and-effect explanation, the staggered extinction of North American megafauna reflects a complex interplay of climatic shifts, human impact, and trophic cascades.

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P18.7

Implications of warming winters on the sedimentation regime of boreal estuaries

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Estuaries have a great ecological, environmental and economical significance as they support diverse ecosystems and act as coastal filters trapping nutrients, organic carbon and detrital material within their sediments. The inner Archipelago Sea is rich in estuaries with complex bathymetry and restricted water exchange, making this environment very sensitive to human pressure. Due to enhanced deposition of organic matter and excessive nutrient loading, the bathymetric depressions of these estuaries suffer from enhanced oxygen depletion, further boosting eutrophication through internal nutrient loading. Establishing sediment fluxes is critical to understanding biogeochemical cycling in such settings, especially under impacts of climate change. In this study, we monitored sediment accumulation rate and composition in the Halikonlahti Estuary (Finland) along a salinity gradient towards the open sea for a two- year period using sediment traps. The concentration and seasonal flux of minerogenic and organic matter, TOC, N, P and trace metals were measured.

Minerogenic matter delivered to the estuary from the inflowing river was observed to accumulate conservatively along the estuary. In contrast, our data show enhanced organic matter and redox sensitive element accumulation within mid-estuary, implying flocculation from dissolved phases in river water. The sediment composition reflects seasonal cycles and interannual variability. Our results show that highest accumulation rates occur during the growth season. Large variation in accumulation is observed between winter seasons. Cold winters with ground frost development and snow cover in the catchment, and ice cover on the estuary, lead to very limited sediment accumulation rates, whereas mild winters with recurrent melting of snow and persistent rainfall lead to sediment accumulation rates closer to summer conditions. This suggests that more frequent mild winters will cause increased sedimentation and organic matter loading to mid-estuary zones, ultimately contributing to the spreading of anoxia.

O19.1 (Keynote)

Development and Assessment of Indicators for Sustainable Groundwater Abstraction under Present and Future Climatic Conditions

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This study develops a decision support system to plan sustainable groundwater abstraction at seven well fields supplying drinking water to Denmark's third largest city. Sustainable abstraction is defined as minimizing ecological impacts while safeguarding water quality. To this end, four quantitative indicators were designed and evaluated using advanced hydrological modelling. These include: (i) effects on groundwater-dependent ecosystems via changes in water tables in legally protected habitats, (ii) streamflow sustainability through impacts on discharge and drought frequency, (iii) aquifer resilience by assessing risks of water quality degradation (e.g., sulfate and chloride intrusion) under over-abstraction, and (iv) urban groundwater levels, highlighting potential benefits of lowering shallow water tables to reduce flood risk in humid areas.

A state-of-the-art dynamic hydrological model with daily time steps was applied to simulate indicator responses under different abstraction scenarios. Both seven existing well fields and three potential new well fields were tested with the sustainability indicators. The combined model–indicator framework enables exploration of optimal abstraction strategies, balancing water supply with ecological and hydrogeological sustainability, and thus providing a practical tool for future water resource planning under increasing demand. The study further investigates how climate change affects the behavior of the indicators and how that compares to stressors from changed abstraction from the well fields.

O19.2

Towards the Development of Digital Twins for Groundwater Management: A Case Study of the Patamäki Aquifer

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A digital twin is a virtual replica of the physical world that is interconnected to a physical entity through bidirectional feedback. The concept gained popularity in the manufacturing industry, but its application in water science is still in its early stages, especially relating to groundwater resource management. This development lag is partially attributed to the fact that the technology required for their development did not exist until recently. Another decisive reason stems from the intrinsic nature of groundwater resources. Globally, many important groundwater sources are confined within large-scale aquifers, whose storage does not change considerably on daily to weekly timescales. Consequently, this means that traditional what-if scenario modelling can provide sufficient information for the management of such systems.

Compared to global resources, Finnish groundwater is mainly contained in small surficial aquifers, including esker and other glaciofluvial formations, making them susceptible to changes in climatic conditions, abstraction rates, and pollution. This relatively high time sensitivity makes the development of digital twins, in theory, feasible for managing such systems.

In this work, we investigate the feasibility of developing a digital twin for groundwater abstraction management in a typical Finnish esker groundwater aquifer, which could support medium-sized utility systems (> 5,000 users). Here, we create a digital twin of the Patamäki esker aquifer, which supplies water to the mid-sized Finnish industrial town of Kokkola. This work presents the conceptual design of the digital twin for the Patamäki aquifer and the groundwater model that serves as a foundation for digital twin development, built using modular open-source groundwater modelling software MODFLOW 6.

O19.3

Quantifying Uncertainty in Shallow Groundwater Monitoring through Sensor Density and Placement Effects on Network Performance

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Rising shallow groundwater levels are an increasing challenge for climate adaptation, threatening both urban infrastructure and agricultural land. Designing effective monitoring networks is therefore a practically important task for utilities and municipalities, yet criteria for sufficient density and placement remain uncertain. While optimisation studies have demonstrated that sparse networks can sometimes reproduce groundwater dynamics (e.g., Ohmer et al. 2019; Meggiorin et al. 2024), little empirical evidence exists at the fine spatial scales where shallow groundwater variability is most pronounced.

This study evaluates the trade-off between sensor density and reconstruction uncertainty using two unusually dense monitoring networks in Denmark: 40 loggers in a village (0.31 km²) and 42 in a rural field site (0.63 km²). Ordinary kriging interpolation was applied to 7000 random logger combinations, with performance assessed against the full networks using Nash–Sutcliffe Efficiency (NSE) and Mean Absolute Error (MAE).

Results show that even sparse networks can yield high accuracy when strategically placed, but uncertainty increases substantially when critical terrain elevation gradients are neglected. At the rural site, as few as 5 sensors/km² occasionally achieved NSE > 0.9 and MAE < 0.3 m, yet performance was highly sensitive to placement. Robust performance required ~15–20 sensors/km². In the urban site, dominated by steep elevation gradients between plateaus, stable performance emerged only from ~25–35 sensors/km², with additional sensors beyond this threshold providing little gain. Across both sites, uncertainties ranged from 0.3–1.2 m depending on density and placement, corresponding to ~4–17% of lateral variation.

These findings provide empirical estimates of the expected uncertainties when reducing or increasing logger numbers in dense shallow groundwater networks. The results demonstrate that while sparser networks can occasionally perform well, consistent accuracy depends on both sensor density and strategic placement along key gradients. This offers practical guidance for water utilities and municipalities on balancing monitoring costs with acceptable levels of uncertainty in climate adaptation planning. Future work will investigate how sensor configuration influences not only interpolation accuracy but also model predictions in machine learning frameworks, further bridging the gap between monitoring design and predictive groundwater modelling.

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O19.4

Implications from 3D hydrogeological modelling workflows in boreal formerly glaciated areas

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This study assesses the applicability of various 3D hydrogeological and groundwater flow modelling workflows for boreal regions shaped by glaciation. Workflows were investigated at GTK using four study sites: Kurikka, Mikkeli, Kangasala, and Oulanka.

In Kurikka, the classification of Quaternary deposits developed by Lunkka et al. (2024) enabled interpretation of large drillhole data from the complex geology, identifying 18 depositional systems that have hydrostratigraphical counterparts. This supported detailed modelling with Groundhog and scalability to the regional applications. In Kangasala, data and methodology comparable to Kurikka was used for esker subsurface hydrostratigraphy modelling including 6 units. In Mikkeli, detailed classification of esker sediments was derived from large drilling dataset that enabled modelling of 17 units with Leapfrog Geo. In Oulanka, simplified classification of sorted valley sediments, direct generalization from drillholes, was sufficient for local-scale modelling with Leapfrog and MODFLOW (GMS), though more detailed classification is recommended for regional integration.

Modelling tools of different software differ in approach: Leapfrog uses contact surface-based modelling, which is less suited to mound-like sedimentary structures such as eskers. The modelling with Leapfrog in environment including both mound and fill-like sediments can be enhanced with point cloud method where dummy point sets were used to guide the contacts of the units. Groundhog's cross-section-based method used is more adaptable to complex environments like buried valleys, although it is more time-consuming when data is limited. Leapfrog was effective for fill-like structures shaped by bedrock topography. Groundwater flow modelling in Kangasala compared FEFLOW and MODFLOW, with MODFLOW-NWT providing the most appropriate match. Consistent settings are essential for realistic cross-platform comparisons.

Local geological conditions, data availability, and specific research objectives affect the selection of workflow. If the modeler has a large drillhole dataset and wants to visualize the 3D model, Leapfrog is suitable. However, if the modeler wants free software with an easy-to-use cross-section-based modelling method, Groundhog can be applied. The hydrostratigraphic classification by Lunkka et al. (2024) proved to be invaluable for complex Quaternary systems, such as the buried valley in Kurikka, and is also applicable to typical esker aquifer settings.

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O19.5

Experiences and observed challenges in using groundwater dating tracers in Finland

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Groundwater is a critical natural resource which is directly impacted by human activity and global change. Facing the unknown long-term changes to groundwater resources globally, the importance of groundwater management increases. Dating tracers measure the residence time that newly recharged groundwater remains in subsurface, and includes conservative tracers directly associated with water molecule (³H) or indirectly by dissolved constituents (e.g., SF₆, ¹⁴C, ⁴He). This study reports the experiences from the use of groundwater dating tracers in Finland within the Fennoscandian Shield. Only few studies have reported the use of groundwater dating tracers in Fennoscandia, but similar challenges related to in-situ or external tracer sources (e.g., Boucher et al. 2015), as observed in geologically similar Canadian Shield, were met.

Seven study sites across Finland were sampled for groundwater dating tracers (³H, ³H/³He, CFCs, SF₆, ¹⁴C, ⁴He), geochemistry, and water stable isotopes, including porous sedimentary aquifers and fractured bedrock reaching up to 1000 m depth from surface. Geochemical characterization suggests the varying influence from ancient brines, surface water infiltration, and natural recharge. Modern groundwater dating tracers (post 1950s) expectedly indicated predominantly young groundwater for shallow depths, but in multiple sites modern tracers were also present in deeper layers and mixed with premodern tracers. Unexpectedly, nearly all sites had very high ⁴He concentrations up to $3.6 \times 10^{-4} \text{ cm}^3(\text{STP})/\text{g}$, which would traditionally indicate very old groundwaters (>>10 ka). Given the simultaneous presence of both modern and premodern tracers, the resulting tracer concentrations would be heavily influenced by either mixing of different water components or poorly understood He fluxes. Observed challenges related to glaciated terrain or crystalline basement is supported by the consistent occurrences within multiple study sites, and our observed high SF₆ concentrations that exceed the historical levels, which have been previously associated with crystalline igneous rocks (Busenberg & Plummer 2000).

Our results bring attention to the necessity of reporting the contradicting results, use of variety of dating tracers, and further research effort needed to understand the groundwater transport and helium dynamics in Fennoscandia. Resolving the ⁴He flux dynamics may be crucial for understanding groundwater age distribution and groundwater management.

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O19.6

Hydrogeochemical characteristics of the groundwater influenced sloping fen in the calcareous rich northern boreal environment

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Groundwater influenced and nutrient rich sloping fens are typical in Kuusamo area in northeastern Finland. These types of fens are affected by both groundwater and surface water including spring floods. In this study, we assess the geochemical composition of peat pore water in a sloping fen located within a carbonate bedrock region, with the dual aim of (1) explaining the influence of groundwater discharge on peat hydrogeochemistry, and (2) comparing the hydrochemical and geochemical signatures with those of northern boreal peatlands underlain by different bedrock types

The study site is a sloping fen Puukkosuo, located in Oulanka in NE Finland near the Oulanka Research station. The 3D structure of the peatland was modelled to understand the flow paths in the peat basin (Åberg et al. 2025.). Four peat cores across the basin were collected to demonstrate the peat composition, humification, and geochemistry (Erhovaara 2023). Pore water samples were collected from the same sampling locations to assess the groundwater effect. Also, seven additional surface and groundwater samples were collected. Trace elements were analysed from all the samples. In addition, pore water samples were analysed for major ion composition, pH, EC, TOC, TC, IC, NO₃+NO₂, NH₄, Tot N, Tot P, and stable isotopic composition of water and $\delta^{13}\text{C}$ (DIC) to assess the effect from adjacent bedrock and groundwater.

Groundwater effect to peat basin in northeastern slope of the fen is indicated by high Ca and Mg concentrations in pore water geochemistry, while the elevated nutrient concentrations in the western edge of the Puukkosuo originates mainly from the surface runoff. Although the broader catchment area lacks extensive carbonate deposits, the presence of carbonate rocks beneath Puukkosuo combined with the sloping fen morphology, indicates that groundwater flow paths significantly influence the geochemical conditions of the fen.

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O19.7

Temporal and spatial variation of metal and nutrient load in Vantaa River, Southern Finland

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The Vantaa River watershed is densely populated and constitutes a reserve water source for water supply in the Helsinki Metropolitan area (1 million people). This research aims to identify the heavy metals and nutrients present in the Vantaa River during the snow free season, measure the weekly heavy metal and nutrient concentrations and test a load estimator software (LOADEST) to determine loads of heavy metals and nutrients at the mouth of the Vantaa River as well as the load to the Baltic Sea.

Weekly water sampling was conducted near a continuous gauging station (Oulunkylä station) between March 2023 and December 2023 resulting 38 samples of the following parameters: major ions, water stable isotopes and trace elements. Samples were also taken from upstream locations of Vantaa River and its tributaries (Kerava River, Lepsämäenjoki River and Tuusula River) in August 2023 to assess the contribution to the heavy metal and nutrient load in the watershed. The USGS application LOADEST was used to estimate total heavy metal and nutrient loads at daily interval over the monitoring period.

Results of the study indicate that the chemical status of the river is over all at moderate state. Most samples of Vantaa River and its tributaries were calcium-magnesium rich waters. The nutrient and metal load of the Vantaa River to the Baltic Sea during the snow free monitoring period is noteworthy. The minimum and maximum daily load for phosphorus was 12.8 kg (24.6.) and 642.21 kg (26.3.), and for nitrogen 666.14 kg (24.6.) and 43 928 kg (13.11.). For the whole period the LOADEST estimated phosphorus load to Vanhankaupunginlahti Bay was 14 000 kg, and for nitrate 2 000 000 kg. Estimated heavy metal load to the Gulf of the Finland was 2 100 000 kg during the monitoring period. Estimated nutrient and metal load showed that a major part of the load occurred in the spring and autumn during high river discharge.

O19.8

Groundwater and surface water contamination by PFAS near a Waste Management Site and landfill leachate treatment Pilot

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Per- and polyfluoroalkyl substances (PFAS) are synthetic, persistent chemicals that have been widely used across various industries and consumer products for decades. Due to their persistence in different terrestrial and aquatic habitats, toxicity and bioaccumulative properties, they pose significant risks to both the environment and human health. Most severe PFAS polluted sites are linked to fluorochemical manufacturing, industrial processes, firefight training and fire suppression sites, landfills, airports and military areas. The aim of the study was to (1) assess the distribution of PFAS in surface water and groundwater in the vicinity of the waste management area and (2) to explore the feasibility of removing PFAS compounds from landfill leachate under field conditions.

The study area consists of a waste management area located in Kerava, Southern Finland with two closed landfills, as well as an ongoing waste recycling operation. One of the landfills is known to have a negative environmental impact through its leachate that seeps into a ditch nearby causing water quality deterioration.

Environmental distribution of PFAS was investigated by 23 samples from streams, ditches and stormwater runoff in different flow conditions. Groundwater pollution was studied with samples from eight observation wells around the legacy landfills. The filtration unit utilizing granular activated carbon (GAC) and modified bentonite was built in a shipping container and was installed on-site. Leachate-loaded ditch water was treated for approximately three months, during which 97 m³ of water was treated.

51 different PFAS compounds were targeted, and the analyses were performed in ALS Czech Republic s.r.o. Additional analyses including Cl, SO₄, NH₄-N, NO₃-N, turbidity, color, pH, alkalinity, TOC, CODMn and EC were performed for groundwater samples and turbidity, pH, CODMn and EC for the first stream samples. Stream water unaffected by contamination from the waste management area had Σ 51PFAS concentrations between 1,6–26 ng l⁻¹ while in the contaminated stream and ditch samples the Σ 51PFAS ranged between 74–1226 ng l⁻¹. Highest PFAS concentrations were observed in the leachate (1322–7358 ng l⁻¹) and in groundwater (4–2749 ng l⁻¹). PFAS concentration in streams and leachate varied with changes in flow conditions. Most frequently detected compounds in the contaminated samples were short-chained PFCA compounds (PFBA, PFPeA, PFHxA). The leachate and stormwater samples contained high proportions of PFCA precursors from the FTCA and FTSA groups.

The findings indicate that surface water and groundwater is polluted in the vicinity of the closed landfill and waste management area, but the contamination is confined to the north side of the activities, where both surface water and groundwater flow is directed. The used filtration method in the pilot was feasible for most compounds while short chained compounds eventually passed through the filtration system.

O19.9 (PRESENTATION CANCELLED)

Using stable isotopes in precipitation to assess climate model simulation skill for hydrogeological impact studies

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Climate models are the main tool used to develop hydrological and hydrogeological climate change impact studies. Previously, climate models have been considered to have the same probability of occurrence. Thus, impact assessments generally used a set of climate models without a comprehensive assessment of their simulation skill. However, given that a group of the latest generation of climate models systematically project warmer conditions than the rest of the models of the same and of previous generations, evaluation of the model skill has become more relevant. As a result, model evaluation requires improvement to become more comprehensive.

This study proposed to include the simulation of stable isotopes in precipitation as a means of evaluating climate model performance. Along with the skill to simulate precipitation and temperature, this will provide a more compressive comparison of the capabilities of the models.

The study will construct isoscapes (stable isotope in precipitation maps) for Finland using machine learning algorithms with climate and physical variables as input. An observation network managed by the University of Oulu, the University of Helsinki, the Finnish Meteorological Institute and the Geological Survey of Finland will be used to train the algorithm. With the algorithm, isoscapes of the last 30 years will be developed for the observations and for the climate models outputs. This approach will allow the comparison of simulations against observations in order to identify better performing models.

The study outcomes are expected to give impact modellers an alternative for the selection of more reliable climate models and to provide robust climate change impact scenarios to be used in hydrological and hydrogeological studies.

O19.10

KOKIS – Kokemäenjoki partial catchment area multi-method monitoring study: long-term changes in hydrogeochemistry, land use and climatic projections

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The KOKIS project focused on the hydrogeochemical state of the Kokemäenjoki river water and the hydrogeological characteristics of the catchment area next to the water intake for the managed aquifer recharge site in Virttaankangas. With over 20 years of monitoring data and a previous multi-isotope study from some 15 years ago, this follow-up study aimed to add to the hydrogeological knowledge of the area with a monthly river water sampling, seasonal river water profiles, groundwater sampling, land use records, satellite imagery and interpretation of climate models, to assess long-term changes in the river water and the effects of climate change in the catchment area. The project was funded by Turun Seudun Vesi Oy (TSV).

The sampling was conducted in 2024, with a total of 12 monthly river water samples analysed for the isotopic compositions of oxygen, hydrogen, carbon (DIC), lithium, strontium, uranium, and lead as well as for a broad geochemical composition and concentrations of TOC and DOC. Same analyses were performed for the groundwater samples collected in August.

The chemical analyses and the isotopic measurements showed seasonality in the $\delta^{18}\text{O}$ and $\delta^2\text{H}$ and the $^{207}\text{Pb}/^{206}\text{Pb}$ values with a spring flow peak, while the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios showed significant variation between the river water and the groundwater sampling. The average isotopic compositions of dissolved strontium and lead are consistent with the average composition of the bedrock in the Kokemäenjoki River catchment area. The $\delta^{13}\text{C}_{\text{DIC}}$ data suggested influences from atmospheric CO_2 , organic matter decomposition, and groundwater discharge to the river water. Uranium and lead isotopic analyses were challenging due to the very low concentrations of U and Pb in the water samples.

Remote sensing (Copernicus Sentinel 1-2 and Landsat 8-9 data) was used to evaluate groundwater discharge zones. Land use data from 2000–2018 (Corine land cover) revealed subtle shifts in forest cover and urban expansion. Climate change impact assessment focused on selecting the best ensemble of climate models and analysing the uncertainties within the models. This combination of study methods, together with the long-term monitoring data available from the Kokemäenjoki River, enables the water utility (TSV) to respond more effectively to future challenges posed by the changing climate.

P19.1

POVADA– Data analysis of groundwater resources

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The purity and sufficiency of water has been almost self-evident, but climate change threatens this important natural resource. Groundwater recharge conditions are altered especially by long droughts, heavy rainfall, and warmer winters. Measured monitoring data and modelling of the effects of these factors on both the quantity and quality of groundwater are needed.

In POVADA– Data analysis of groundwater resources project, groundwater geologists and engineers combine their expertise to safeguard the quality and quantity of groundwater in different climate scenarios. The project's measures focus on private and public water supply in Finnish Lapland, Kainuu and Northern Ostrobothnia. The project is co-funded by the European Union as European Regional Development Fund (ERDF). Duration of the project is from the beginning of September 2025 to the end of November 2027.

The project will create a model based on regional monitoring data of the amount and safe residence time of groundwater in different types of aquifers under current and future climate scenarios.

Monitoring data is collected from target areas for example from the open databases of Finnish Environment Institute, the Finnish Meteorological Institute and GTK. The climate models created in the project will also serve as data sources for modelling.

The model to be created can be used to improve preparedness for climate change and other potential risks. The results of the work can be utilized not only in the project area but also nationally.

In addition, a groundwater flow measurement method will be developed to improve understanding of, for example, the impact of water abstraction and changes caused by climate change on the amount of water and water quality in the aquifer.

The project provides the water supply sector with information and suggestions for adapting to climate change. The project will produce an information package based on modeled data, which includes a recommendation time for rainwater infiltration into groundwater based on soil data, i.e. residence time for different types of aquifers. A sufficient residence time guarantees the high quality of groundwater and its suitability for domestic use. And by land use planning it is possible to prevent groundwater pollution if the most vulnerable areas are protected.

Gathering of the data is currently underway. The results will be published as articles and reports and communicated in webinars for water utilities and authorities. The project and its results will also be presented at seminars.

Consortium of POVADA:

The Geological Survey of Finland (GTK), University of Oulu, The Unit of Measurement Technology (Mity), LUT University (Lappeenranta–Lahti University of Technology LUT), CEMIS Centre for Measurement and Information Systems (CEMIS), CSC – IT Center for Science (CSC), Location Innovation Hub (LIH).

P19.2

Intelligent Groundwater Management Solutions for Mining Environments – The AWE Project Approach

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The Arctic Water Excellence (AWE) project addresses the urgent need for advanced, cost-effective water management solutions in water-intensive industries, with a particular focus on the mining sector in Northern and Eastern Finland. As mining operations expand and environmental regulations tighten, there is a growing demand for more comprehensive, real-time, and data-driven approaches to monitoring and managing the impacts of mining on groundwater systems.

Key challenges for groundwater monitoring in mining environments include the lack of comprehensive baseline data and the low spatial and temporal coverage of groundwater observations. Even globally, traditional groundwater monitoring planning often relies on expert interpretation of maps and other limited data, which can result in both insufficient and excessive monitoring, increasing costs and potentially leading to a limited understanding of subsurface water dynamics (see e.g., Gladish et al. 2023). Our research directly addresses these challenges by developing and piloting new strategies for digitalisation and optimisation of groundwater monitoring in collaboration with mining companies.

Our current work, based on data from two Finnish mine sites, focuses on supplementing groundwater observations using existing datasets, spatial statistical analyses and machine learning techniques. By integrating advanced data processing, we enable more systematic and targeted monitoring network design, focusing resources on the most critical locations and parameters for groundwater risk management. This not only improves the detection and prevention of adverse groundwater impacts, but also supports more efficient allocation of monitoring resources throughout the mine lifecycle.

Through these efforts, we aim to deliver new expertise and services for intelligent groundwater management in mining, bring out more value from existing groundwater monitoring datasets and support the sector's transition towards more sustainable groundwater monitoring practices.

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P19.3

How are groundwater-surface water interactions and carbon transport interconnected on a river valley scale?

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Observations from cold regions indicate delayed freeze-up, earlier snowmelt, and increasing precipitation and runoff, underscoring the dynamic nature of groundwater (GW)–surface water (SW) interactions, yet their hydrogeochemical role in the carbon cycle remains insufficiently understood. At the Oulanka Research Station, Finland, we investigated GW–SW interconnections and dissolved carbon (DOC and DIC) transport in the Haaralaminkangas river-valley aquifer using nine observation wells (2022–2025), supported by a 3D hydrostratigraphic model and multivariate statistical analyses. Seasonal recharge strongly controlled GW levels, with snowmelt and autumn rainfall driving the largest responses: wells with groundwater tables closer to the surface (2–8 m b.g.s.) fluctuated by <0.5 m, while those with deeper groundwater tables (10–14 m b.g.s.) varied by up to 2 m. The Oulankajoki River supplied DOC-rich water (6–8 mg L⁻¹ total organic carbon) that was attenuated and mineralised to DIC in adjacent wells, whereas hillslope recharge generated episodic DOC peaks (up to 9.6 mg L⁻¹) during autumn flushing. Pond- and fen-connected wells maintained moderate DOC but elevated DIC (8–12 mg L⁻¹), and deeper groundwater tables accumulated both DOC and DIC during winter baseflow, reflecting storage and redox transformation. Geological controls were equally important: glaciofluvial sand and gravel facilitated rapid infiltration and DOC transport, while underlying dolostone–limestone bedrock enhanced carbonate dissolution, buffering groundwater chemistry and promoting DIC accumulation. These results preliminarily demonstrate that under climate warming, with shifts in snowmelt timing and intensified autumn rainfall, GW–SW connectivity will increasingly enhance DOC pulses and intensify DIC cycling in northern aquifers. To better elucidate these processes, MODFLOW will be applied to simulate groundwater flow and its links to carbon transport, while Amanzi/ATS will be used to capture integrated hydrology, hydrogeology, and carbon cycling across multiple spatial and temporal scales.

P19.4

Numerical Modeling of Groundwater Budget under Alternative Boundary Scenarios

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In regional groundwater flow modeling, boundary conditions are critical controls. They are often determining water budgets and head distribution. We evaluate their influence through a steady-state MODFLOW-NWT model of the deep Salento aquifer (southern Italy), a karstic system underlying the Salento Peninsula, bounded by the Adriatic Sea to the east, the Ionian Sea to the west, and the Murge Hills to the north. The model discretization included seven hydrostratigraphic units and accounts for distributed recharge, evapotranspiration, and pumping, with calibration based on PEST and sensitivity analysis.

Scenario 1 with constant head at the Murge hills, mixed coastal boundaries, produced the most balanced and observationally consistent flow directions and discharge zones. In Scenario 2, replacing the northern constant head with a conductance-limited general head boundary yields a plausible, stable solution that represents finite northern recharge. In Scenario 3, assigning conductance-based boundaries to both coasts, there is preserved mass balance but produced unrealistic north–south gradients and southern-biased discharge. Results of the sensitivity analysis show that recharge and pumping control the main aquifer response, while conductance of boundary conditions is a secondary but important control on flow distribution.

Overall, explicitly testing alternative BCs is essential for robust groundwater budgets and regional assessments.

P19.5

Numerical investigation on the reliability of analytically calculated tracer-swept pore volumes in fractured rock

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Efficient geothermal energy production requires that injected fluids sweep through a fracture network with sufficient volume and contact area for heat exchange. Tracer tests are widely used to estimate tracer-swept pore volumes and, thereby, to assess reservoir performance. However, there is a knowledge gap in understanding how different reservoir geometries and heterogeneities within the fracture network affect the accuracy of the tracer-swept pore volume estimations.

This work presents an ongoing numerical study using discrete fracture network simulations to directly compare actual and analytically calculated tracer-swept pore volumes. A systematic exploration is carried out across a wide range of reservoir geometries, connectivity patterns, and injection–production protocols. This approach provides a structured framework for assessing the reliability of tracer-swept pore volume calculations, beyond case-specific observations.

The study aims to clarify under which reservoir conditions the analytical approach may under- or overestimate tracer-swept pore volumes, and how these deviations might influence the evaluation of reservoir performance. By identifying the circumstances that lead to biased volume estimates, the work contributes to improving the interpretation of tracer test results and guiding their application in fractured reservoir characterization.

O20.1 (Keynote)

The quest for a clean solution – challenges with mine water treatment in subarctic climate

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Luossavaara Kiirunavaara Aktiebolag (LKAB) mines iron ore at three mines in northern Sweden: Kiruna, Svappavaara and Malmberget. The mines discharge process water with elevated concentrations of nitrate, sulfate and uranium, to their recipients. The recipient concentrations of total dissolved U exceed the EQS value at all sites. In Kiruna, $\text{NO}_3\text{-N}$ exceeds the EQS. For SO_4 , there is no current EQS value, but given the concentration in the recipients, it is regarded as an ecologically relevant compound.

The water management is similar at all sites. Process water is recirculated in the inner as well as the outer water circuits. Despite intensive recycling of water, a surplus, resulting from the dewatering of the mine and from precipitation, is discharged to the recipient.

NO_3 from undetonated explosives dissolves into the mine water. NO_3 is also transported to the processing plants with the ore, and dissolve into the process water during the wet milling process.

SO_4 originates primarily from the dissolution of anhydrite associated to the ore.

The U source is uraninite mainly present in the side rock. Upon mining this U is oxidized and transformed into more soluble U(VI). The bioavailable concentration (UO_2^{2+}) is far below the EQS value, but current legislation uses total dissolved U concentration for comparison.

LKAB has investigated several water treatment techniques for NO_3 , SO_4 and U. For NO_3 , the biological MBBR technique (Moving Bed Biofilm Reactor) has been tested in pilot scale with good results. However, denitrifying bacteria must be supported with phosphorus, giving elevated phosphate concentrations in the treated water. In order not to deteriorate the environmental status in the recipients, no increase in phosphate in discharge water can be accepted.

For SO_4 , two technologies have been tested. The precipitation of SO_4 as ettringite after the addition of sodium aluminate led to the formation of unmanageable large amounts of a high pH sludge. Biological treatment of SO_4 on the other hand requires significant addition of carbon source and is not considered suitable for LKAB process water.

Ion exchange has been tested for the removal of U, but the adsorption to the ion exchange resin turned out to be irreversible. Various membrane techniques, that would remove U as well as nitrate and SO_4 , have been tested, but the presence of colloidal particles and high calcium levels in the process water make these techniques unsuitable.

Pilot testing with U removal using precipitation, flocculation and sedimentation has been successful. However, the resulting sludge exceeds current limits for handling and deposition of radioactive material.

Current and future work thus focuses on developing a technique that reduces NO_3 without increasing phosphorus. We are proceeding with pre-planning of a U treatment plant. For SO_4 treatment, we keep following the development in the industry.

O20.2

Observations working with neutral rock drainage and metal leaching in Finland

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Neutral rock drainage and metal leaching (NRDML) is potentially the most common harmful mine drainage type in Finland. In a project related to financial guarantees and water responsibilities (Laakso et al. 2022), the background study included the analysis of Finnish mine closure plans and drainage types. In eight of the ten studied cases at least one part of the operating mine site generated NRDML. Three out of five studied new permitting cases were predicted to generate NRDML. Rather similar observations were made in literature review concerning historical sites. Despite the common occurrence of NRDML, environmental assessments still commonly focus into the risk of acid rock drainage (ARD) instead of NRDML.

NRDML is formed in similar way as ARDML, but neutralizing capacity keeps pH in the neutral or slightly alkaline territory. Higher pH allows more sorption, but it does not guarantee good water quality. Some metals or metalloids that are released in sulfide mineral oxidation, are sorbed rather well from neutral pore water, but some metals or metalloids, like As, Ni or Zn, remain typically relatively well soluble in neutral pH. Quite commonly, sorption is also controlled by the availability of co-precipitators, like iron.

Definition of inert waste in European commission decision 2009/359/EC or Finnish extractive waste decree (190/2013) also steer the focus into towards the ARDML risk. Also, best available technique conclusions of MWEI BREF document mostly refer to acid generation potential as a basis for extractive waste facility design (Garbarino et al. 2018). On the other hand, different drainage water types are recognized more widely in the background chapters of MWEI BREF document.

Simplified classifications based on one or two factors are not good enough basis for planning extractive waste management. Site-specific multi-factors assessment is always necessary.

This paper reviews good practices for early identification of NRDML risk, including kinetic testing and models following the kinetic tests. The role of sorption and factors impacting sorption are also reviewed.

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O20.3

Geochemical behaviour of rare earth elements in mine tailings under neutral mine drainage conditions

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The Critical Raw Materials (CRM) Act stresses the urgent need to increase the domestic production of CRM in the EU. However, there is limited knowledge about the near-surface geochemistry, bioavailability, and toxicity of nearly all CRM, making it challenging to extract minerals sustainably with a low environmental impact. Given the substantial data required, the USGS recommends a prioritisation approach for future research on CRM geochemistry in the terrestrial environment (White et al. 2024). Rare earth elements (REEs) are classified as the elements with the highest supply chain vulnerability and, at the same time, as emerging contaminants of concern. According to the USGS, environmental research regarding REEs should have a high priority compared to other CRMs (White et al. 2024). Current research on REEs in mine waste has focused largely on acid mine drainage (AMD), showing high mobility of REEs at pH values below 4.5 (Lozano et al. 2020). In contrast, their behaviour in neutral mine drainage (NMD) remains poorly constrained (Gwenzi et al. 2018).

This study focused on one apatite iron ore tailings storage facility (TSF) in northern Sweden, including tailings solids, groundwater and monitoring well water. Three intact tailings cores were collected in 2024, and 95 subsamples were analysed for total concentration. Of these samples, 15 were further examined using XRD, SEM-EDS, and three samples underwent analysis with automated mineralogy. Dissolved concentrations of REEs (<0.2 µm) in groundwater and water from monitoring wells were obtained during field campaigns from 2024 to 2025. REE concentrations were quantified by ICP-MS (solids) and ICP-SFMS (waters).

The major REE bearing minerals in the tailings were apatite, monazite and allanite. Mineralogical studies together with geochemical data indicate that the REEs in these geochemical settings were stable, with low mobility of REE in the mine drainage. Thus, tailings profiles displayed similar chondrite normalised REE patterns as the original ore (LREE enrichment, negative Eu anomalies). A significant correlation between REE and P ($R^2 = 0.74-0.96$) was found in all three tailings depth profiles. The anoxic near-neutral groundwater (pH 6.8) contained low dissolved concentrations of REEs (average: 0.28 µg/L). Thin section analysis from the tailings cores confirmed that REEs remained hosted in unaltered apatite and monazite, supporting their stability in the apatite iron ore TSF.

These results add valuable insight into the prioritization approach suggested by USGS, indicating that REE geochemistry in apatite iron ore under NMD should have lower priority compared to REE in AMD with pH below 4.5.

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O20.4

Mobility of metal(loid)s from mining sludge: Insights from laboratory leaching tests and implications for potential sludge stabilization

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Mining wastewater treatment processes generate large volumes of sludge that often contain potentially toxic metal(loid)s (MLs) (Matebese et al. 2024). Understanding the mobility of these contaminants is critical for assessing environmental risks and developing effective stabilization and/or remediation strategies. In this study, we investigated the mobility of MLs in calcite-dominated sludge produced after Fenton and liming treatment of wastewater from a mine tailings impoundment.

Results from a six-step sequential extraction showed that most major elements were hosted in the residual fraction, while some Ca, Fe, and S were also leached from the exchangeable and carbonate fractions, likely due to the dissolution of soluble minerals such as calcite (CaCO_3) and gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) (Tessier et al. 1979). The most labile MLs were Cd, Co, and Cu, and these exhibited the highest concentrations in the exchangeable and carbonate fractions. Trace amounts of these MLs together with Ni, and Pb were also leached from the amorphous and crystalline iron oxides fraction, suggesting their inclusion in secondary iron-oxyhydroxide phases. Due to the presence of potentially toxic MLs in the more mobile fractions, which may pose environmental risks, additional stabilization measures are necessary.

One potential approach to stabilize this potentially toxic mining sludge involved solidification using a cementitious binder (Jouini et al. 2022; Liu et al. 2018). To assess the mobility of MLs in such a cementitious system, a batch leaching test was conducted on sludge samples solidified with Ordinary Portland Cement (OPC) and ground granulated blast furnace slag (GGBFS). The results indicated that OPC increased the mobility of most MLs, potentially due to its high pH (~12) and the presence of elevated concentrations of certain MLs within the OPC itself (e.g., As, Cr, Mo). In contrast, GGBFS demonstrated lower mobilization of MLs, particularly for the most labile elements such as Co, Cr, Cu, Ni and Pb. However, this does not necessarily indicate long-term immobilization, as GGBFS remains alkaline (pH= ~8-11) and may still promote ML mobilization over time. Therefore, long-term leaching tests are essential to fully evaluate the immobilization potential of these binders.

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O20.5

Metal Removal in Lake Hosiojärvi Using Nordic Microalgae and Wood Ash: Insights from Laboratory and Mesocosm Experiments

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The long-term environmental risk posed by contaminated lake systems in mining-impacted regions has increased interest in nature-based water treatment solutions. This study evaluated whether wood ash can stimulate algal growth and, when combined with Nordic microalgae enhance metal removal from the nutrient-poor Lake Hosiojärvi in Northern Sweden using laboratory microcosms and in situ mesocosms. Laboratory microcosms tested combinations of two algal species (*Chlorella vulgaris* 13-1 and *Coelastrella* sp. 3-4), known for metal removal efficiency (Spain et al. 2021), with two wood ash types (Ash D and Ash P) in lake water. A native strain, *Desmodesmus* sp., already present in lake water, served as control. The microcosms included four setups: (a) lake water only (control), (b) lake water + ash, (c) lake water + algae, and (d) lake water + ash + algae. Algal growth was tracked via fluorescence ratios (daily) and chlorophyll-a concentrations (endpoint measurement) over 25 days.

Results showed that *Chlorella vulgaris* 13-1 responded strongly to Ash P, while *Coelastrella* sp. 3-4 grew better with Ash D. Ash-only microcosms supported limited biomass growth, likely due to stimulation of native algae but lower initial biomass relative to the inoculated microcosms. To evaluate in situ performance, a mesocosm system was installed in Lake Hosiojärvi and monitored for 21 days. The experimental setup included: (c) lake water + algae, and (d) lake water + ash + algae. Chlorophyll-a increased in all setups except in lake water + algae mesocosms, confirming consistency with laboratory results and the enhancing effect of ash addition.

Dissolved metals (<0.22 µm) were measured via ICP-MS to assess metal uptake by the different strains. In the laboratory microcosms, zinc (Zn) removal ranged from 29% to 88%, with the highest removal seen in lake water + ash microcosms. Zn was also removed in algae-only and ash + algae microcosms, though variability is observed between strains (29%-70%). Nickel (Ni) removal ranged from 38% to 86%, with the highest observed in the microcosm with lake water + ash + algae (*Chlorella* + Ash P). Copper (Cu) concentrations increased in ash-containing samples, possibly due to leaching from the ash. The persistence of Cu in the dissolved phase may be influenced by factors such as the presence of free ions or complexation, requiring further study. In the mesocosm system, Zn and Ni concentrations declined over time, and Cu increased in all ash-amended setups, reflecting microcosm results.

These findings suggest that specific combinations of algae and ash can enhance biomass growth and metal removal in oligotrophic systems. However, responses were strain- and ash-type dependent, highlighting the need for pre-screening to match suitable pairs for site-specific application. Future studies should optimize this pairing and assess long-term and seasonal performance under variable lake conditions

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O20.6

Co-disposal of tailings and waste rock in an arctic setting; risk management opportunities and challenges

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The co-disposal of waste rock and tailings as an emerging or novel concept is increasingly being considered by both regulatory bodies, and operators within the mining industry as a potential alternative to traditional tailings facilities such as slurry dams. The main driver for this interest has been largely geotechnical and as a reactive response to a number of recent catastrophic failures of slurry tailings dams. To date however the development of holistic approaches to assess the relative benefits and applicability of this method to different climates and operational settings (such as the arctic environment) are currently not well understood or documented.

In general technical reviews of co-disposal methods consider geotechnical risk (stability) as the focus of primary study, risk assessment and feasibility. This focus on stability tends to drive conceptual design considerations towards the use of dewatered or filtered tailings and inclusion of engineered drainage. However, this being the case, the co-dependant nature of geochemical (environmental) risk with geotechnical risk requires careful consideration as this co-dependency provides both risks and opportunities. Given many hard rock metal mines produce tailings and waste rock with appreciable sulfide content, geochemical risks are manifest when considering structures designed to be unsaturated and well drained.

This paper provides an integrated overview of both key geochemical and geotechnical risks related to co-disposal, and outline how these interact with unsaturated hydrogeological characteristics. In addition the paper indicates how risks can be assessed to inform the engineering design concept, and how relative benefits can be assessed when comparing the method to traditional methods of tailings and waste rock disposal.

Results are presented from an instrumented field trial carried out at a site undertaking detailed design studies of a large co-disposal facility that uses co-mingled (blended) tailings and waste rock, where the technique is being considered as a feasible option to reduce both geotechnical and geochemical risk. Results from the field trial indicate that co-disposal results in creation of an effective barrier to oxygen ingress which is positive for geochemical risk management, but that as well as reducing oxygen ingress, drain down of the material at sub surface depth can occur at a faster rate than the additional flux of infiltration from surface, which is advantageous from geotechnical perspective.

O20.7

Co-disposal of waste rock and tailings – methods and site-specific testing

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In this study, the co-disposal methods for extractive waste were assessed, focusing on combined deposition of waste rock and tailings in a single waste storage facility. Conducted within the Geological Survey of Finland's SMARTTEST project, the study includes a literature review of case studies and practical testing, emphasizing applicability of co-disposal to Finnish conditions.

Co-disposal of extractive waste involves placing coarse waste rock together with fine grained tailings, either pre-mixed or sequentially. The potential benefits can include improved geotechnical and geochemical stability, lower construction and maintenance costs, enhanced storage efficiency, and smaller required facility size. Properties related to geotechnical stability may be enhanced through faster consolidation, which allows earlier commence of closure activities. Geochemical stability may be enhanced through reduced oxygen and water infiltration, resulting in decreased generation of acid mine drainage. Challenges can be related to optimizing mixing ratios and methods, achieving homogeneous mixing, and potential restrictions on future reuse of waste materials.

Several co-disposal methods exist, including mixing waste streams before deposition (co-mixing), allowing mixing during deposition (co-mingling), and constructing internal berms or cells within waste areas (co-placement). Internationally, methods like pumped co-mixed deposition, underground backfilling, and the construction of tailings cells within waste rock embankments are relatively common. In Finland, large-scale co-disposal of extractive waste has not yet been implemented. However, it is being considered in several mining projects under development.

Research suggests that tailings cells and layered co-disposal are the most practical co-disposal options. These options are also among the methods considered at the Finnish mine projects planning to utilize co-disposal. Co-disposal method selection depends on site-specific operational, economic, and material considerations, requiring site specific investigations. Testing involves laboratory and field trials, supported by numerical modelling. It includes material characterization, mixing and deposition experiments, and environmental assessment. Laboratory tests, following international standards, underpin site-specific experiments like column tests, while field trials validate constructability and geotechnical performance. Numerical modelling helps scale results to full-scale applications.

The study can facilitate the adoption of co-disposal of extractive waste in future mining projects in Finland, supporting more sustainable and efficient mine waste management. It highlights the wide spectrum of potential methods and importance of site-specific testing to ensure technical feasibility and environmental safety.

O20.8

Silica-based surface coating as a novel approach to inhibit sulfide oxidation and prevent Acid Mine Drainage formation during mining operations

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The increasing demand for base and precious metals continues to generate substantial volumes of mine waste, including sulfidic waste rock, necessitating effective Acid Mine Drainage (AMD) mitigation strategies. To prevent AMD during operation, proactive measures must be implemented, as cover systems applied only at closure are insufficient. Among various passive approaches, surface passivation or inhibition of sulfide oxidation is a promising, innovative technology. It works by forming stable, protective coatings on sulfide minerals, thereby inhibiting their oxidation and maintaining circumneutral drainage pH.

Silica coating is particularly effective, as it provides long-term stability and neutralization, while benefiting from its abundance and availability from diverse geological and industrial sources. Moreover, silica layers are generally inert and insoluble under neutral to mildly acidic conditions, making them well-suited for AMD prevention. To assess the viability of silica coating, we address two key research questions in our study: (1) *Does Si treatment effectively inhibit sulfide oxidation and suppress metals release?* and (2) *What materials can serve as suitable and sustainable sources of dissolved Si?*

In a kinetic column leaching experiment, pyritic waste rock (11 wt.% S) from an operating copper mine was subjected to 11 weeks of water leaching and air exposure, after which selected columns were treated with silica solution, with and without H₂O₂ pre-oxidation. One column consisting of untreated waste rock served as a reference. Following silica treatment, the treated columns maintained circumneutral leachate pH. In contrast, sulfide oxidation occurred in untreated waste rock, resulting in an acidic pH (~4) and elevated metal concentrations in the leachate, as confirmed by mineralogical analysis, which showed the dissolution of pyrite (FeS₂). Silica treatment effectively suppressed the release of metals (e.g., Al, Fe, Cu, Co, Mn, Ni), and the formation of stable silica (SiO₂) coating successfully inhibited pyrite oxidation. Integration of isotope analysis with leachate chemistry and mineralogy supported these findings, including the identification of sulfur sources in the leachate and associated geochemical processes.

To evaluate the long-term sustainability of silica coatings and explore opportunities for circularity in mine waste management and synergy with Carbon Capture, Utilization, and Storage (CCUS), we conducted additional batch leaching tests using siliceous side streams from mine sites as alternative silica sources for pyrite inhibition. These tests aimed to identify optimal leaching conditions to release dissolved silica from such materials. Our findings suggest that silica release can be enhanced under carbonated conditions. Finally, silica treatment, when coupled with on-site utilization of silicate-bearing side streams, could provide an effective and sustainable strategy for mitigating AMD during mining operations.

O20.9

Experiences in backfilling

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Backfilling of open pits with waste rock is becoming a common topic of discussion in environmental permit handlings in Finland. This paper discusses experiences in backfill planning and describes issues that should be considered carefully before decision making.

Firstly, the Mining Act (621/2011) states clearly that hindering possible future use of mineralization is prohibited. Therefore mineral potential below or in immediate closeness of the pit must be well studied.

Environmentally more significant is the waste rock (backfill) geochemistry, together with the pit wall geochemistry. The initial rock quality is only a part of the picture: oxidation or weathering status of the waste rock at the time of the pit flooding must be well understood. Many of the oxidation products are not necessarily stable in the water saturated conditions. This means that rock storage time before flooding the pit, impacts critically to the environmental performance of the backfilled open pit.

Often the initial idea is to backfill the more harmful waste rocks, in hope of less costly on waste storage and closure structures. Cost savings are most likely achievable in situation, where rock can be deposited to the pit “fresh” and the pit can be quickly flooded.

Also backfilling in already fully formed pit lakes is not unproblematic and should only be done after careful consideration. Even though placing highly sulphidic waste material in waterlogged condition is considered to be environmentally best practise to prevent oxidation, this is not always the case. In already acidified lakes the sulphidic waste material can be oxidized even under water cover due to reduction/oxidation cycle of iron.

Groundwater rebound speed and final level must be also known, and in some cases artificial filling may be beneficial from the environmental performance perspective. Pit-lake or backfilled pit is both a receptor of load in its catchment area and a load source for the downstream environment. Therefore, the hydrological contact between the pit and the surrounding environment must be well understood.

O20.10

Assessing Nordic mine waste for carbon storage potential

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Global CO₂ emissions are increasing and bending the curve will require widescale innovation in the development and implementation of sustainable energy sources, phasing out fossil fuels, and carbon capture and storage technologies. Global carbon storage capacity is necessary to retain captured carbon from the atmosphere and to aim for *geological net zero*, meaning that for every tonne of CO₂ generated from fossil sources one tonne of CO₂ should be permanently restored to the solid Earth. Carbon storage is currently operating on a megaton scale but needs to expand to a several gigatonne scale of storage per year by 2050 to meet 1.5C warming goals set forth by the IPCC. The mining industry has a role in supporting technological advancements in our transition to sustainable energy technologies and innovative strategies in mine waste management could lead to the mining industry reducing their carbon footprint. Suitable mine waste materials can be used to store carbon by means of carbon mineralisation.

Carbon captured from the atmosphere, or flue gas can be stored safely and permanently through carbon mineralisation; in which carbon atoms bond with divalent cations through an exothermic reaction, producing carbonate minerals. Mine waste has been proposed as an ideal source of divalent cations as it is economically produced at a vast scale, and its fine particle size increases reaction efficiency. Using mine waste for carbon mineralisation also has the potential to neutralise tailings, reduce acid mine drainage, and could allow for enhanced metal recovery. However, the suitability of mine waste for carbon mineralisation depends on its chemical and mineralogical composition.

This study investigates ten different tailing types across four Nordic mines; Kevitsa, Aitik, Kiruna and Viscaria, all of which are associated with different deposit types; magmatic Ni-Cu-PGE, porphyry Cu-Au, iron oxide-apatite, and stratiform Cu-Fe, respectively. The tailings were assessed for their carbon storage potential based on their chemical and mineralogical compositions. Metal oxide quantity determines the carbon storage potential; however, the physicochemical properties of the waste minerals determine the true utility these tailings have for carbon mineralisation. The results could serve as an analogue for similar mine sites globally, to assess the potential of their waste offering a pathway to sequester carbon and valorise mine waste.

O20.11

Ecosystem restoration in mining waste areas utilizing side streams of local the bio-circular economy

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Covering and landscaping waste rock sites is an essential part of mine closure. Forest till is the most used material for covering, as it helps limit the leaching of water and oxygen through the waste rock. When the goal is also to enhance vegetation development on covered waste rock sites, organic matter is needed in addition to till.

The Biopeitto -projects (<https://www.luke.fi/en/projects/biopeitto3>) have been studying cover solutions that utilize regional side streams from the bio-circular economy. Additionally, meadow species adapted to northern conditions and different vegetation establishment methods have been tested. In addition to pot-grown seedlings and seeds, meadow cuttings, forest floor material, and transplanted tree seedlings have been used. Study sites have been established in Rautuvaara, Kevitsa and Pahtavaara mining sites.

Used side-stream substrates, including sewage sludge compost, ashes of energy production and various biochars, significantly improved plant survival, germination, growth, and spreading. Species that spread effectively from seeds include for example *Silene dioica* and *Leucanthemum vulgare*. A wide variety of flowering plant species, such as *Trifolium pratense* and *Ranunculus acris*, emerged when using meadow cuttings. Healthy vegetation also improves soil water retention, enhancing evaporation during the growing season while reducing the amount of water filtering through the cover structures. Biodiversity and ecological restoration at waste rock sites can be further enhanced by utilizing geomorphology and microtopography. Adding decaying wood and rocks collected from the surrounding area supports plant growth and soil microbiome, all of which contribute to restoration success.

O20.12

Mobile-manufactured biochar in mine closure, costly yet carbon-negative

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Biochar has shown to increase plant growth by 20-200 % in central Lapland mining area, which makes it an attractive component for future mine closure solutions. The Biopeitto projects in Lapland focused on establishing a value chain to implement a biocover solution for a mining site, with a specific interest in using biochar derived from waste wood as a growing medium supplement. The network of actors included a wastewater treatment plant, a demolition wood processing company and energy factor as owners of the raw materials, a supplier of pyrolysis equipment, logistic operators, a local plant nursery and the mine as the end user of the solution. In the value chain pilot, the demolition wood was pyrolysed into biochar, composted with the sewage sludge and the produced growing medium was used as growth media in the mine waste site.

A life cycle costing (LCC) and life cycle assessment (LCA) were undertaken to evaluate the production processes and value chains of four growing media formulations composed of composted sewage sludge, fly ash, peat, till, and demolition wood-derived biochar.

Incorporating biochar into a compost–till mixture, at a 10% volumetric share, increased costs by 51–71%, resulting in a price of €28.60 m⁻³. The least expensive scenario was the compost–ash–till mixture, with a cost of €16.76 m⁻³. Environmental impacts were monetized based on their carbon dioxide equivalent (CO₂eq) emissions as determined through LCA (€52.56 CO₂eq t⁻¹). When accounting for the long-term carbon storage potential of the materials, emissions were highest for the peat–till-based formulation (74.7 kg CO₂eq m⁻³) and lowest for the biochar-amended mixture, which exhibited negative emissions (-49.7 kg CO₂eq m⁻³). Thus, the biochar-based solution functioned as a carbon sink.

The study demonstrated that: 1) growing media developed from circular bioeconomy-based approaches generated lower emissions compared with traditional peat-based substrates; 2) biochar-based growing media exhibited net negative climate emissions; and 3) although the price of biochar-based growing media was comparatively high, measures were proposed to mitigate these costs. The beneficial impacts of biochar on plant growth in mine-affected areas have been documented in prior research; however, these findings were not incorporated into the environmental or economic evaluations of the present study.

P20.1

Suitability of Dry Tailings Deposition Techniques in Northern Conditions – Field Testing within the SMARTTEST Project

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In the ore beneficiation process, tailings are generated and stored in a dedicated tailings storage area within the mining site. The most common disposal method for tailings is wet disposal, where tailings are transported as slurry with process water into a tailings pond. The water content of the slurry typically ranges between 60–75%. In the pond, solid particles settle to the bottom while water separates to the surface, from where it is directed via decant wells to a clarification pond and then either returned to the beneficiation process or discharged into natural water bodies after water treatment.

Wet disposal retains a significant amount of water in the tailings, and the storage areas require embankment structures that may be prone to failure. In addition, tailings water needs to be managed and often also treated to prevent contamination of surface or ground water bodies near the tailings facility. For improved safety, space efficiency, and reduced environmental impacts, disposal techniques based on dewatering such as dry stacking of filtered tailings and paste deposition are becoming more common. These methods offer advantages in terms of stability and reduced land use, but their adoption has been slowed by the additional costs of dewatering.

Dry stacking techniques provide a sustainable and controlled solution for tailings management, especially in northern regions where cold climate, seasonal variability, and water management affect material behaviour and structural stability (Neuffer 2015). As part of the SMARTTEST project, the Geological Survey of Finland is conducting a field pilot in the GTK SMARTTEST test field, Outokumpu, to assess the applicability of dry stacking under humid Nordic conditions.

The field test combines continuous climate monitoring via a weather station, precise structural measurements using Lidar technology, water quality analyses of the drainage and seepage waters discharging through the tailings, and laboratory analyses of the geotechnical, geochemical, and mineralogical properties of the tailings before and after deposition. Field measurements are used to monitor the behavior of the stacked material, including compaction, permeability, and mechanical and geochemical stability.

The results of the pilot will be compiled into a service package to support the testing and implementation of dry and paste tailings deposition techniques under field conditions. The project promotes circular economy solutions in the mining sector and provides a knowledge base for environmental risk management in northern environments (Geological Survey of Finland 2024).

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P20.2

Fire on the Reykjanes Peninsula - five years of eruptions at Fagradalsfjall and Sundhnúkur, SW Iceland

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The Reykjanes Peninsula hosts a series of volcanic lineaments that have produced recurrent eruptive episodes over the past 4000 years. After nearly 800 years of quiescence, twelve eruptions have occurred since 2021 along the Fagradalsfjall and Sundhnúkur lineaments, marking the onset of a new cycle of volcanic unrest on the peninsula. Here, we summarise the ongoing magmatic reawakening of the peninsula and report on the recent eruptive activity at the Fagradalsfjall volcanic lineament between March 2021 and August 2023 and at the Sundhnúkur crater row since December 2023. Using geochemical data and seismic tomography, we evaluate the current state of magma storage beneath the peninsula and discuss whether the ongoing activity is sourced from a single reservoir or multiple zones within the crust and upper mantle.

Geochemical data from the 2021 Fagradalsfjall eruption reveal considerable compositional fluctuations during the early stages, suggesting injection of heterogeneous mantle melts into a lower-crustal reservoir at 10–12 km depth, possibly months to years before eruption. The 2023–2024 Sundhnúkur eruptions initially showed compositional similarities to earlier events, but the magmas shifted to more evolved compositions over the course of 2024 and into 2025.

Geophysical observations provide evidence supporting a common deep source reservoir for the 2021–23 and 2023–25 magmas, linked by a connected plumbing system. Seismic tomography reveals a high-Vp/Vs anomaly at depths of 9–12 km beneath Fagradalsfjall, extending laterally for ~10 km. This anomaly is interpreted as a lower-crustal magma accumulation zone that has been supplying magma to all eruptions since 2021, with dykes propagating along inclined pathways to reach vents, including those at Sundhnúkur.

Since much of Iceland's population lives on the Reykjanes Peninsula, understanding the dynamics of these eruptions is essential for effective hazard management and eruption forecasting. We conclude with an assessment of the main volcanic hazards in the region and their implications for local infrastructure and communities.

O21.1 (Keynote)

Do analogues of the Archean exist on modern Earth? New evidence for the presence of vertical tectonics and the absence of life in the Eoarchean of SW Greenland

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Fieldwork remains the cornerstone of geological research, allowing direct observation of rocks in their natural settings, providing the foundation for reconstructing Earth's history. However, the polymetamorphic evolution of Archean cratons often overprints original field relations and compromises their geochemical information through deformation, metamorphism, and metasomatism, obscuring tectonic and magmatic interpretations of the Archean rock record. Progress in this field therefore requires a broad interdisciplinary approach using cutting edge isotope geochemistry and thermodynamic modelling. Nevertheless, correct field interpretations hinge critically on detailed structural observations and metamorphic petrology without which erroneous conclusions will be drawn.

Unfortunately, these complications to the earliest rock record frequently result in speculative claims by narrow specialists. This commonly results in "high impact" publications with interpretations that extend far beyond what the data can reasonably support if the degraded and strongly modified state of the rocks were acknowledged. Such overreach clouds the literature, slows genuine advancement, and can even cause scientific retrogression. The Eoarchean Itsaq Gneiss Complex (IGC) is the oldest part of the North Atlantic Craton and includes the >3.7 Ga Isua Supracrustal Belt and the Akilia Island, which are prime examples of controversial claims that confuse our knowledge of the early Earth.

In this presentation, I draw on my experience during more than a dozen summers of fieldwork in SW Greenland to give examples of controversial interpretations that have caused significant confusion. These include key localities, such as the Isua stromatolite, conglomerate, and turbidite, and the Akilia Island BIF, which all require reinterpretations considering new geochronology, granulite-facies metamorphism, and evidence for significant deformation and late-stage structural and metasomatic processes.

Absence of evidence for life is not evidence for absence of life, however, the recently recognized overprinting of the Eoarchean rocks of the IGC during the Meso- to Neoarchean strongly questions the appropriateness of using this rock record to study early habitability of our planet. Furthermore, the implications of the high-grade metamorphic and strong metasomatic overprinting of all components of the IGC challenges the previous interpretation of an arc-like geodynamic environment for the oldest supracrustal rock record on Earth. In contrast, detailed thermodynamic modelling of magmatic systems accounting for the metamorphic and metasomatic modifications of their protoliths indicate the presence of hot and dry parental magmas during the first half of the Archean Eon. This is in line with estimates of a higher mantle potential temperature, higher radioactive heat flux within the crust, and the observation of highly refractory dunite cumulates derived from komatiitic magmas in the SW Greenland.

O21.2

Geochemistry of the Macquarie Island North Mountain ultramafic intrusion and implications on its formation process

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Macquarie Island is the only sub-aerial exposure of *in situ* mid-ocean ridge oceanic crust on Earth. Transpressional forces have uplifted and exposed the tilted fraction that includes both upper mantle and crustal units (e.g., Goscombe et al. 2024). The ophiolite was formed at a slow-spreading ridge where crustal accretion continued through multiple magmatic events.

Macquarie Island's North Mountain is an arcuate shaped ultramafic intrusion measuring 40-70 m x 350 m size. The intrusion formed between 8.6 and 8.2 Ma, representing a second stage of magmatism after the initial phase of crust formation (Goscombe et al. 2024). The intrusion cuts the transition from gabbro to the sheeted dike complex and has a 5 m wide chilled margin. The intrusion exposes a wehrlitic crystallization sequence of olivine-clinopyroxene-plagioclase, atypical for nominally dry mid-ocean ridge setting (e.g., Koepke et al. 2009). To date it is the only reported oceanic crustal hundred-meter scale ultramafic intrusion with both a wehrlitic crystallization sequence and a chilled margin, globally.

The geochemistry of the samples indicate that the intrusion has formed through olivine accumulation and has experienced melt-rock reactions subsequently. Suppression of plagioclase crystallization, elevated Fe³⁺ in Cr-spinel and the presence of magmatic amphibole indicate a melt enriched in H₂O which can be considered rare for a mid-ocean ridge setting. Poikilitic clinopyroxene in the North Mountain samples show strong and complex chemical zonation indicating modification through melt-rock reactions, in contrast to observations in nature or experimentally, as clinopyroxene is not detected to exhibit chemical zonation in crustal wehrlites formed through crystal accumulation (e.g. Gahlan et al. 2011; Koepke et al. 2009).

Both structural and geochemical findings imply that the formation process of the intrusion includes features different to any other reported olivine-rich cumulate of the oceanic crust. We speculate that similar intrusions might be common in oceanic crust globally as ophiolite occurrences mainly represent supra-subduction zone setting and sample material from gabbroic crust of mid-ocean ridges is more limited.

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O21.3

The High Arctic Large Igneous Province: insights into Early Cretaceous magmatism on Svalbard

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The High Arctic Large Igneous Province (HALIP) was emplaced during the Early Cretaceous. Remnants of the HALIP occur all over the circum-Arctic, including Arctic Canada, northern Greenland, the Arctic Ocean, Franz Josef Land, and Svalbard. The timing and magma evolution of the HALIP has been studied for decades, but Svalbard is underrepresented in the published literature. The HALIP was emplaced during three magmatic pulses, at ca. 126 – 120 Ma, 94.5 – 90 Ma, and 84 – 78 Ma, however, only the oldest pulse has been noted on Svalbard (Sartell et al. in press). Geochemical studies have mainly been focused on the Canadian Arctic, with several studies published in recent years (e.g., Bédard et al. 2021). In comparison only eight whole-rock geochemical analyses have been published from Svalbard to date (Nejbert et al. 2011).

To improve our understanding the emplacement of the HALIP, the geochronology and geochemistry of the dolerites on Svalbard has been the focus of an ongoing PhD project. Field campaigns in the years 2020 – 2025 have resulted in over 150 regional samples collected, as well as over 100 samples for a detailed case-study in central Spitsbergen. Whole-rock geochemical analysis, U-Pb geochronology and petrological studies are in progress. During the expeditions, high resolution-drone images for photogrammetry were also acquired. These resulting digital outcrop models are used for thickness estimates of sills and to put the analytical results into a three-dimensional perspective.

Here, we present the results obtained to date. This includes a U-Pb baddeleyite age from a HALIP sill in central Spitsbergen, digital outcrop models, and an extensive whole-rock geochemical dataset from Svalbard.

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O21.4

Crustal cannibalism – the role of assimilation in creating and recycling felsic crust

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The generation of large volumes of igneous felsic crust, especially during the Archean, remains a central question in understanding the evolution of our planet. Two primary but contrasting mechanisms are commonly invoked: (1) fractional crystallization of mafic magmas versus (2) partial melting of pre-existing crust. Both mechanisms explain some observations, but also face significant limitations—fractional crystallization implies vast volumes of mafic cumulates that are often missing, while partial melting requires a substantial and often elusive heat source. A hybrid model, assimilation-fractional crystallization (AFC), offers a compelling alternative, whereby primitive magmas act as the heat source whereas assimilation of (partial melts) of older crust generate felsic compositions without excessive cumulate formation.

Our recent study at Katla volcano, Iceland, demonstrates the viability of AFC processes in generating silicic melts (Troll et al. 2025). In Iceland, meteoric water circulation and hydrothermal alteration impart a distinct low- $\delta^{18}\text{O}$ isotopic signature into the pre-existing igneous rocks. Many of Katla's felsic volcanic rocks show clear geochemical evidence of notable assimilation of altered rocks from the caldera and underlying crust, exemplifying a “self-cannibalizing volcano” that recycled its own altered edifice rocks to produce evolved magmas.

Thermodynamic modeling further supports the feasibility of assimilation as an important contributor of mass into magmatic systems. Primitive magmas can incorporate crustal material in amounts exceeding their own mass while retaining basaltic compositions (Heinonen et al. 2022). This realization opens the possibility for significant crustal recycling and felsic crust generation even in settings with limited pre-existing felsic crust.

We aim to expand this approach by modeling AFC processes all the way from ultramafic to felsic compositions using variable trace element compatibility and concentrations. This will allow us to quantify the relative contributions of parental magma and assimilants through thermodynamically-constrained chemical mass balance. Our preliminary results suggest that in evolved igneous systems, elements compatible with the magma may predominantly originate from the assimilated crust, underscoring the potential importance of assimilation processes in shaping Earth's felsic crust across geologic time.

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O21.5

Unravelling the paleovolcanic setting of the Pyhäsalmi volcanic complex in western Finland through volcanic-facies mapping

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This study provides the first systematic description of volcanic facies in the vicinity of the world-class Pyhäsalmi Zn–Cu–Au–Ag deposit (>70Mt, production 1962–2022; Mäki et al. 2015). The results allow for improved reconstruction of the paleovolcanic setting and the linkage between volcanism and ore-forming processes.

Outcrop mapping and relogging of old drill core in the Pyhäsalmi volcanic complex reveals 18 lithofacies. Volcanism occurred in a submarine, below-wave-base setting and was mainly effusive and non-fragmental, forming lavas and (crypto) domes in association with mafic volcanism in a sedimentary basin. Contrary to previous results, we interpret fragmental rocks as peperitic and hyaloclastic facies emplaced at dome margins, and their resedimented equivalents, rather than as primary pyroclastic deposits from rhyolitic explosive eruptions. Lack of primary pyroclastics could result from non-explosive growth of dome volcanoes, or of high hydrostatic pressure constraining volcanic explosions in a deep-water setting. We suggest that volcanic activity was both preceded and succeeded by submarine clastic sedimentation. The volcanogenic sedimentary facies comprises volcanoclastic turbiditic mass-transport deposits intercalated with hemipelagic sediments, indicating deposition in a deep-water, below-wave-base and submarine slope/shelf proximal setting. Clasts of felsic volcanic debris in this facies may represent either distal fallout from subaerial explosive eruptions, or resedimented eruption-fed pyroclastic debris (pumice) from collapsed eruption plumes. The locally abundant mafic flows (pillow lavas) and mafic fissure eruptions (submarine fountain eruptions) are driven by extensional magmatism on the seafloor.

The Pyhäsalmi base metal deposit formed as sub-seafloor replacement style mineralization within the brecciated facies at the margins of the rhyolite domes or lavas and adjacent to the overlying clastic volcanogenic sedimentary facies. Sulfides may have formed during quiescent periods or within hemipelagic sediments that may have acted as a seal between permeable clastic facies and impermeable sedimentary and mafic flows, thereby enhancing hydrothermal circulation and metal precipitation.

The volcanic facies architecture of the Pyhäsalmi volcanic complex suggest an extensional volcanic arc basin setting, where the known sulfide deposits (Pyhäsalmi and Mulliköräme) may have originally formed at slightly different stratigraphic levels in an otherwise lateral (contemporaneous) volcanic succession. Improved facies understanding enables belt-scale mineral system analysis and opens new search space for VMS exploration in the underexplored Vihanti–Pyhäsalmi belt.

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O21.6

Eruptive iron oxide beds in the Vattuvaara deposit, Narken, Northern Sweden

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The Northern Norrbotten Ore Province is most famous for its giant Paleoproterozoic Kiruna-type iron-oxide-apatite (IOA) deposits, with the largest bodies concentrated in a corridor between Kiruna and Gällivare. The Narken deposits, ca. 100 km east of Gällivare, occur in an N-S-trending belt and comprise isolated iron oxide mineralisation hosted by strongly metasomatized sedimentary rocks of the Sammakovaara Group (Frietsch 1972; Bergman et al. 2001). The Narken deposits have been described as hydrothermal breccia- or vein-type mineralisation, spatially associated with extensive silicification, epidotization and chloritization of the host rocks (Frietsch 1972; Martinsson et al. 2016). The iron-oxide mineralisation contains euhedral, abraded and partly fragmented magnetite (commonly altered to hematite) and tabular hematite (Martinsson 2009; Martinsson et al. 2016). In this field-based study, we document primary depositional structures from the Vattuvaara iron oxide deposit located south of the village of Narken.

Three distinct iron oxide units have been recognized: (1) reverse-graded iron oxide crystal tuff (1–50 mm) unconformably overlying the basal sediment; (2) low-angle, cross-bedded iron oxide beds that are commonly reverse-graded; and (3) an iron oxide-rich lithic breccia. The breccia is composed of angular blocks of the basal sediment (10 cm–3 m) with long axes parallel to bedding that are supported by a crystal-rich iron oxide matrix that shows grading and layering, with disturbed layering proximal to the lithic clasts.

These depositional features are typical for repeated near-vent pyroclastic base surges, and we tentatively interpret the mineralised sequence at Vattuvaara as a proximal phreatomagmatic iron-oxide maar related tuff ring setting. This interpretation is consistent with the abraded and fragmented magnetite reported by Martinsson et al. (2016).

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O21.7

The Theodolit Plateau Intrusive Suite: ultrapotassic monzonite–syenite magmatism in the East Greenland Caledonides

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Ultrapotassic plutonic rocks are rare markers of mantle–crust interaction in collisional orogens and have only sparingly been reported from Greenland, most notably in eastern Milne Land within the East Greenland Caledonides. New data from Clavering Ø identify a distinctive suite of quartz-deficient, foliated monzonites, monzodiorites, and syenites, here defined as the Theodolit Plateau Intrusive Suite (TPIS). These rocks are dominated by K-feldspar and mafic silicates and show extreme potassic enrichment (K_2O up to 11 wt%; $K_2O/Na_2O = 3–6$). Whole-rock geochemistry places the suite firmly in the ultrapotassic field, with strong enrichment in large-ion lithophile and light rare earth elements, high-field strength element depletion, and negative Eu-anomalies, distinguishing them from coeval Caledonian S-type granites and the metasedimentary basement.

Precise U–Pb zircon dating (SIMS) constrains their emplacement to ~430 Ma, synchronous with peak Caledonian metamorphism, confirming syn-tectonic emplacement during the waning stages of thrusting. We interpret the TPIS as derived from partial melting of a mantle source metasomatised by subducted Krummedal-type sediments, triggered by slab break-off and asthenospheric upwelling. Recognition of the TPIS expands the distribution of ultrapotassic magmatism in Greenland beyond Milne Land and establishes it as the most coherent (ultra)potassic suite yet identified in the East Greenland Caledonides.

O21.8

Small crystals, big eruptions: Quartz phenocrysts as archives of caldera-forming processes in the Permian Drammen Caldera, Oslo Rift, Norway

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Caldera-forming eruptions are among the most dangerous and catastrophic volcanic phenomena, yet the related magma reservoir processes are poorly understood. In the Permo-Carboniferous Oslo Rift in Southeastern Norway, there are at least 15 calderas, several of which have preserved pyroclastic deposits. Here we focus on a >450 m thick rhyolitic ignimbrite succession in the 7 x 7 km Drammen Caldera, located 40 km southwest of Oslo. We present field observations, petrography, and geochemical analyses, with an emphasis on primary quartz phenocrysts.

Ignimbrite stratigraphy in the Drammen Caldera comprises the high-grade, phenocryst-rich Lian Formation (25–30% crystals) and the moderate- to low-grade, phenocryst-poor Sørumlia Formation (1–2% crystals). The Lian Formation records a large, sustained pyroclastic eruption that tapped a crystal-rich part of the reservoir, whereas the Sørumlia Formation was deposited over several smaller, highly explosive eruptions sourced from crystal-poor magma batches. In both formations, primary quartz phenocrysts occur as euhedral, rounded, and embayed crystals, and range in size from 50 to 2000 μm .

Cathodoluminescence (CL) imaging of primary quartz phenocrysts reveals widespread oscillatory zoning, and several crystals show a distinct core with resorption margin, indicating changing magma reservoir conditions during crystal growth. To investigate the origin of the zoning, we conducted in situ oxygen and silicon isotope analyses. The primary quartz has an average $\delta^{18}\text{O}$ value of $8.03 \pm 0.23\text{‰}$, suggesting assimilation of high- $\delta^{18}\text{O}$ Lower Palaeozoic sedimentary rocks surrounding the caldera. As most intracrystal values are indistinguishable within the analytical uncertainty, we interpret assimilation to have occurred prior to quartz growth. Quartz phenocrysts yield an average $\delta^{30}\text{Si}$ value of $-0.08 \pm 0.43\text{‰}$. Like oxygen, silicon isotopes show no significant inter- or intracrystal variation, indicating isotopic homogeneity of the melt prior to the ignimbrite-forming eruptions. The combination of textural complexity and isotopic homogeneity in primary quartz phenocrysts provides new insights into felsic magma reservoir processes in the Oslo Rift.

O21.9

High-Resolution Seismic Geomorphology of the Vøring Marginal High Constrained by IODP Expedition 396 Borehole Data and Iceland Field Analogues

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Historic large volume basaltic eruptions in Iceland provide important insights into the understanding of ancient lava flow fields in outcrops or seismic reflection data. NE Atlantic continental breakup in the Paleogene was associated with massive basaltic magmatism and global warming. The offshore volcanic deposits are up to 6 km thick (e.g., seaward-dipping reflectors) and cored by scientific boreholes (e.g., ODP 642E). Massive onshore breakup-related basalt deposits are exposed in east Greenland, the Faroes and in the UK. Hot-spot magmatism has continued since breakup and is manifested by subaerial seafloor spreading on Iceland today. IODP Exp. 396 drilled two sites, U1571 and U1572, on the Vøring Marginal High to understand the volcanic emplacement processes and environments. The sites were located based on interpretation of industry-standard 3D seismic reflection data (CVX1101) targeting a faulted and a pitted top-basalt domain, respectively. About 100 m of basalt flows were cored at each site, with a very good recovery (c. 80%). Wireline and acoustic and resistivity image logs were acquired in U1571B. Subsequently, a high-resolution P-Cable 3D seismic cube of 1.7x10.4 km was acquired across the two sites during the UiT CAGE22-5 cruise, and a slightly smaller time-laps cube was acquired during the UiT-IG24-8 cruise. The processed bin size is 6.25x6.25 m with a dominant bandwidth of 50-200 Hz. The high-resolution 3D seismic data were interpreted using the method of igneous seismic geomorphology. Two main domains are clearly distinguished. The faulted domain above the apex of the Skoll High is overlapped by a non-faulted sequence in the west with a distinctly different seismic morphology of the top basalt surface. The central part of this so-called pitted domain consists of small basins separated by ridges. A lobate structure with arcuate ridges is present in the west, whereas elongated undulatory high-amplitude structures are identified in a depression separating the two domains. The borehole data reveals a sequence of early Eocene simple basalt flows and thin inter-basalt sediments likely deposited in a coastal environment. In Iceland, we have conducted field work and drone surveys guided by remote sensing data to compare the morphologies from field with the seismic geomorphological data. Focus has been on studying flow lobes of Laki and Eldgjá flow fields in the south and Holuhraun and Laxárdalur flow fields in the north, all of which were formed by large flood lava eruptions. On the flat coastal domains, the flow fields display a variety of morphologies, including rootless cones, lava rise pits, lava breakouts with compressional ridges, and elongated tubes in the front of the main flow field. The historic flow fields resemble what we image on the high-resolution seismic and borehole data. We conclude that the historic large-volume Icelandic flow fields are appropriate field analogues to the ancestral Vøring Marginal High basalt flows.

O21.10

Multi-year oxygen isotope record of Fagradalsfjall and Sundhnúkur Fires, Iceland: constraints on mantle source and magmatic evolution

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The Reykjanes Peninsula (RP), SW Iceland, hosts several linear volcanic vent systems that have been periodically active in post-glacial time. In 2021, following 781 years of dormancy, the RP entered a new eruption period with the onset of the 2021-23 Fagradalsfjall Fires, which comprised three effusive eruptions (the Geldingadalir, Meradalir, and Litli-Hrútur events). Late in 2023, volcanic activity shifted westwards to the Sundhnúkur vent system, marking the onset of the Sundhnúkur Fires, which to date comprise seven effusive eruptions. To better understand the origins and evolution of the magma feeding these eruptions, we present $^{18}\text{O}/^{16}\text{O}$ data (as $\delta^{18}\text{O}$ values) and major and trace element data for lava and tephra samples from seven eruptions that took place between 2021 and 2024. Using these data, we constructed an almost four-year-long time-series of magmatic $\delta^{18}\text{O}$ values for the Fagradalsfjall and Sundhnúkur Fires. This dataset represents an exceptionally long record of oxygen isotope variations for an active Icelandic basaltic rift system, providing unique insight into the $\delta^{18}\text{O}$ composition of the mantle beneath SW Iceland and magma differentiation processes. The data reveal subtle changes in $\delta^{18}\text{O}$ values, with $\delta^{18}\text{O}$ values similar to mid-ocean ridge basalt (MORB) dominating in 2022 and 2023. The exceptionally fresh nature of the samples coupled with their MORB-like $\delta^{18}\text{O}$ values make these samples a benchmark for mantle $\delta^{18}\text{O}$ values in the North Atlantic region. However, from late 2023 onwards, $\delta^{18}\text{O}$ values show a change that coincides with a shift to shallower (~5 km) magma residence prior to eruption, which suggests that oxygen isotope ratios can be modified by crustal differentiation processes over timescales of less than a year.

The Sveinar Cone Rows Are Not a Single Eruption: New Tephrochronological Evidence Reveals a Multiphase Holocene History, NE Iceland

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The Rauðuborgir-Sveinar-Randhólar-Rauðhólar (RSRR) lineament forms one of the most striking volcanic features of the Northern Volcanic Zone (NVZ) in Northeast Iceland. Extending ~75 km as a chain of ~22 crater rows, it has long been interpreted as the surface expression of a single fissure eruption that took place ~11ka yrs BP, making it the longest volcanic fissure in Iceland. Early structural work within the Sveinar grabens, part of the lineament, emphasised early to mid-Holocene faulting but did not recognise late Holocene volcanotectonic events. Similarly, other stratigraphic studies concluded that the Sveinar and related craters erupted >6-9ka yrs BP. However, recent reconnaissance studies and our 2025 field campaign reveal a far more complex eruptive and tectonic history.

Here, we present new stratigraphical, field, and tephrochronological evidence demonstrating the asynchronous formation of the Sveinar cone rows (SCR), including previously unrecognised late Holocene volcanotectonic activity. The Sveinar graben system hosts several cone rows with distinct eruptive ages. The main SCR (Vegasveinar, Sveinar and Ytri-Sveinar) were previously dated to ~6-8ka yrs BP, while our observations reveal a ~6-7ka yrs BP age for Sveinar, since the ~7ka Hekla-5 is absent from soil profiles on top of the lava. However, the Ytri-Sveinar cone row, situated north of the former, is considerably younger, at ~2ka yrs BP, an age verified by the presence of the 2.5ka Hverfjall tephra under the Ytri-Sveinar lavas and its scoria fall deposit. The Vegasveinar cone row, by High1 and south of Sveinar, is dated at ~11ka yrs BP, because the ~10.8ka Askja-A (Skolli) tephra layer is present in the soil resting on top of scoria from the cone.

These results provide the first direct evidence that the SCR, and thus the RSRR lineament, are not a product of a single eruption but rather constructed by multiple discrete eruptive events spanning at least 9 millennia, from ~11ka until ~2ka yrs BP. Moreover, associated grabens and normal faults exhibit a similarly prolonged development, with some faults cutting across the ~2ka Ytri-Sveinar lava and cones, confirming tectonic activity in this system younger than previously recognised. This study highlights the need to reconsider existing models of fissure eruption development and rift propagation in Iceland. By refining the eruptive chronology of the Sveinar cone rows, we demonstrate that activity persisted far longer than assumed, overturning the long-standing view of a single early Holocene fissure eruption and establishing instead a multiphase eruptive history that continued into the last two millennia. Thus, we contribute to a broader understanding of the coupling between magmatism and tectonism in the NVZ and provide new constraints on the Holocene evolution of rifted volcanic terrains.

O21.12

The magmatism of 2021-23 Fagradalsfjall Fires, Reykjanes Volcanic Belt, Iceland

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On the evening of 19 March 2021, after 781 years of quiescence, the Reykjanes Volcanic Belt (RVB), Iceland, entered into its 4th Eruption Period in the last 4000 yrs when an eruption began on a 180-m-long linear vent system at the Fagradalsfjall volcanic complex. This event also marked the onset of the 2021-23 Fagradalsfjall Fires, which featured three effusive eruptions: 19.03-18.09.2021 at Geldingadalir, 03-21.08.2022 at Meradalir, and 10.07-05.08.2023 at Litli-Hrútur. Collectively they erupted $135 \times 10^6 \text{ m}^3$ (DRE) of mostly enriched, olivine tholeiite (8-8.5 wt% MgO) magma. However, the 2021 Geldingadalir eruption initially expelled depleted olivine tholeiite magma. These magmas were extracted from a $\sim 100 \text{ km}^3$ crystal-mush-rich magma storage zone situated at 9-12 km depth beneath Fagradalsfjall (e.g., Troll et al. 2024). Major element analyses of groundmass glass in tephra from the 2021 Geldingadalir eruption reveal that during the first 12 days, the melts were depleted olivine tholeiites ($8.02 \pm 0.12 \text{ wt\% MgO}$, $n=85$) with a $\text{K}_2\text{O}/\text{TiO}_2$ value of ~ 0.15 , which is consistent with the highest $\text{K}_2\text{O}/\text{TiO}_2$ melts ($0.015\text{-}0.16$) erupted during the Holocene on the RVB. From day 13, the $\text{K}_2\text{O}/\text{TiO}_2$ value of the erupted melt at Geldingadalir ($8.19 \pm 0.18 \text{ wt\% MgO}$; $n=50$) steadily increased until day 39, when it plateaued at a value of ~ 0.25 . For the remaining 4 months (i.e., days 39-180) of the 2021 eruption ($8.43 \pm 0.25 \text{ wt\% MgO}$, $n=117$) and throughout the 2022 Meradalir ($7.59 \pm 0.26 \text{ wt\% MgO}$, $n=172$) and 2023 Litli-Hrútur events ($7.35 \pm 0.21 \text{ wt\% MgO}$, $n=72$), the erupted melt $\text{K}_2\text{O}/\text{TiO}_2$ value was remarkably steady at ~ 0.25 . This is a uniquely high $\text{K}_2\text{O}/\text{TiO}_2$ value for basaltic melts with these MgO contents, as melts with 6.5-8.5 wt% MgO within the axial rift in Iceland typically have $\text{K}_2\text{O}/\text{TiO}_2$ values of ~ 0.15 or lower and all values are < 0.20 . The same applies to the 6.5-8.5 wt% MgO alkalic basalt melts from Hekla and Vestmannaeyjar volcanic systems (i.e., $\text{K}_2\text{O}/\text{TiO}_2 < 0.20$). The only 6.5-8.5 wt% MgO melts with higher $\text{K}_2\text{O}/\text{TiO}_2$ values (average, 0.49 ± 0.29) are melt inclusions from an effusive basalt eruption in the Snæfellsnes Volcanic Belt (Kahl et al. 2021). It is therefore unlikely that the enriched melt composition erupted during the 2021-23 Fagradalsfjall Fires was delivered to the surface by the Holocene volcanism in Iceland and is instead a new addition its magmatism.

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O21.13

Origin of Silicic Magmatism at the Katla Volcanic Complex, South Iceland

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The Katla volcano is a bimodal caldera complex within Iceland's basalt-dominated Eastern Volcanic Zone. To unravel the petrogenesis of silica-rich rocks from Katla, we provide new $\delta^{18}\text{O}$ values for almost 60 basaltic, intermediate, and high-silica eruptive rocks, including a number of partially melted felsic xenoliths (Troll et al. 2025). The basaltic samples display a range in bulk-rock $\delta^{18}\text{O}$ values from +4.3 to +8.5‰ (n=17) and the sparse intermediate samples from +4.1 to +5.9‰ (n=3). In turn, silicic rock samples and feldspar separates range from +2.7 to +6.4‰ (n=38), whereas the felsic xenoliths yield the lowest values from -4.9 to -2.3‰ (n=4). The majority (95%) of the Katla silicic volcanics have $\delta^{18}\text{O}$ values below typical MORB (ie. $\leq 5.0\text{‰}$), ruling out an origin via closed-system fractional crystallisation from the basaltic magmas. We utilised the new $\delta^{18}\text{O}$ values to model possible assimilation and fractional crystallisation (AFC) scenarios. The results indicate an early stage of FC/AFC at deep- to mid-crustal levels, followed by assimilation of low- $\delta^{18}\text{O}$ hydrothermally-altered sub-volcanic materials similar to the low- $\delta^{18}\text{O}$ felsic xenoliths at shallow crustal levels. Such a two-stage magma evolution is consistent with available geophysical and geobarometry studies at Katla, indicating mid- to deep-crustal as well as shallow-crustal magma domains. Importantly, mafic rocks show dominantly MORB-like $\delta^{18}\text{O}$ values, whereas low $\delta^{18}\text{O}$ values occur essentially in silicic rocks only. This implies that the low- $\delta^{18}\text{O}$ values at Katla are imposed by interaction with Icelandic crust, rather than reflecting low $\delta^{18}\text{O}$ in the underlying mantle sources.

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P21.2

Determining the mantle $\delta^{18}\text{O}$ signature of the 1730-1736 Timanfaya eruption, Lanzarote

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The ca. 1730-1736 volcanism on Lanzarote is a matter of contention as some authors argue that the volcanic activity contradicts the hot spot model for the Canary archipelago. In addition, the compositional changes in the eruption sequence led to discussion on whether mantle source processes or crustal influences are the controlling factors for the observed compositional variability. Here we present 34 new $\delta^{18}\text{O}$ values of whole rocks and olivine separates, coupled with new major and trace element data, from the second half of the Timanfaya eruption (ca. 1733-1736). We use the data to test if crustal assimilation can be detected and to establish if primitive compositions display a MORB or a plume-type signature. Our results show a range of +4.9 to +5.7‰ (± 0.12 ; 2 sigma) for sampled lavas, 4.6 to 5.2‰ for olivine (5.0 to 5.5‰ equilibrium melt values), and -9.5 to +23.7‰ for crustal xenoliths. The more evolved lava samples show mildly elevated $\delta^{18}\text{O}$ values relative to closed system fractional crystallisation trends, implying that crustal input occurred, but was localised and volumetrically limited ($\leq 5\%$). The most primitive samples in the collected lava suite yield whole rock values of $\sim +4.9\%$ and the combined lava samples average to $\sim +5.3\%$, thus providing a primary mantle derived magmatic range of +4.9 to +5.3‰. The most primitive values of the sampled lava suite are thus inconsistent with a pure upper mantle derivation (+5.5 to +5.7‰ for Atlantic MORB), but require a mildly lower $\delta^{18}\text{O}$ plume-type mantle input, implying that plume-fed hot-spot magmatism is a key contributor to volcanism on Lanzarote Island.

P21.3

Mantle heterogeneity beneath the Oslo Rift revealed by the early basaltic stage of the Skagerrak Large Igneous Province

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The Oslo Rift is the northernmost reach of the Skagerrak Large Igneous Province (SkLIP), where mafic volcanism began around 300 Ma with the emplacement of the so-called “B1” basalts. Erupted over a relatively brief interval of ca. 1–2 Myr, B1 lavas now form successions up to 1500 m thick and provide a precious window into early rift evolution and mantle dynamics at the onset of SkLIP activity (Neumann et al. 2025).

We present a rift-scale geochemical overview of B1 lavas from five main lava piles: Brunlanes, Skien, Vestfold, Jeløya, and Krokskogen. The lavas geochemistry displays a pronounced latitudinal gradient: highly alkaline products (melilitites to alkali basalts) dominate the southern sections, while tholeiitic compositions are found at Krokskogen in the north, despite broadly coeval emplacement across the region. This transition is accompanied by changes in trace element abundances and radiogenic isotopes, implying contribution of up to four distinct mantle sources.

The strongly alkaline Brunlanes lavas reflect are kimberlite-like, with low initial Sr–Nd isotope ratios (LoNd type; Hyung et al. 2023). We interpret this as a deep, mildly carbonated mantle plume source, although a role for metasomatic lithospheric domains cannot be entirely ruled out.

A second mantle component shows HIMU-like Sr–Nd–Pb isotopic signatures and high incompatible-element contents, whereas a third, enriched-mantle (EM-type) source supplies a less incompatible-element-rich contribution. The Skien B1 series appears to record melting of a hybrid mantle involving all three components, while Vestfold and Jeløya basalts reflect mixing between HIMU-like and EM-type sources. We propose that the lower lithosphere beneath the Skien–Vestfold–Jeløya area consisted of EM-type garnet peridotite that was metasomatized by HIMU-like melts long before SkLIP initiation, forming enriched veins subsequently tapped during B1 volcanism. These melts likely originated at ≥ 140 km depths during or just prior to lithospheric thinning.

A fourth, more depleted mantle source that escaped metasomatic enrichment was accessed only by the tholeiitic basalts of Krokskogen in the north. This source probably formed at shallower depths and may indicate rapid thermal erosion of the northern lithosphere.

Disentangling the multi-source evolution of the B1 basalts is essential for reconstructing the earliest magmatic stages of the SkLIP and evaluating their potential role—through CO₂ release—in Carboniferous–Permian climate perturbations.

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P21.4

Multispectral remote sensing of hydrothermal alteration zones in the El Lago Volcanic Complex

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The Plio-Holocene El Lago Volcanic Complex (ELVC), located in the Central Volcanic Zone of northern Chile, is of great geological interest because it challenges our understanding of iron oxide-apatite (IOA) deposit formation and its connection to hydrothermal processes. The ELVC consists of a central volcanic plug, surrounded by six magnetite ore bodies. The host sequence, comprised of andesite lava flows and pyroclastic rocks, shows widespread hydrothermal alteration, spatially linked to some ore bodies.

The origin of the ELVC remains one of the most controversial among all IOA-type deposits worldwide, as two schools of thought exist that actively debate whether the iron-ore lava flows formed through high-temperature magmatic processes (Tornos et al. 2017) or sub-magmatic hydrothermal replacement (Dare et al. 2015), or a combination of both (Troll et al. 2019).

Iron ore bodies are limited in volume compared to extensive surficial alteration; however, the effects and style of hydrothermal alteration have received comparatively little attention. To better understand the alteration and its relation to ore genesis, we combine orbital multispectral imagery with laboratory analyses, including the identification and quantification of alteration minerals in rock samples for ground-truth comparison.

To determine the areal extent of hydrothermally altered materials and to delineate the ore bodies and potential zones of in-situ oxidation at ELVC, we defined our input dataset using ASTER and Landsat 8 OLI/TIRS satellite data processed in the Google Earth Engine platform. Results were displayed as intensity maps using color scales to represent abundance of key minerals.

Spectral data, combined with field observations and laboratory analyses of collected rock samples from El Lago, reveals pervasive acid-sulfate alteration, characterized by K-rich clays, quartz, native sulfur, gypsum, among others. The intensity of alteration shows marked spatial variability, with higher abundance near some of the ore bodies. Our approach distinguishes hydrothermally altered rocks from unaltered materials at different stages of alteration, providing valuable insights into their spatial distribution and potential relationships with outcropping ore bodies. Therefore, this integrated approach not only advances our understanding of the processes associated with the ELVC but is also relevant for similar systems.

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P21.5

Hydrothermal alteration mapping in the Purico and Chajnantor domes using multispectral satellite remote sensing

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The Pleistocene Purico-Chascón Volcanic Complex (PCVC), located in the Central Volcanic Zone of northern Chile, formed approximately 1.4–0.9 Myr ago with the eruption of the Purico Ignimbrite. Approximately 80–100 km³ of pyroclastic material erupted to form this ignimbrite. Less voluminous andesitic to dacitic domes also formed within the complex, with ages between 0.98 and 0.18 Ma (Burns 2014), including, from north to south, Purico, Dome D, Chajnantor (Cerro), Negro, Chascón and Áspero. These domes exhibit conical morphologies and are interpreted to derive from mafic magma recharges that mixed with high-silica melts (Francis et al. 1984; Davidson et al. 1990).

At present, intense fumarolic activity and extensive surficial hydrothermal alteration are recognized at the PCVC. Notably, some of the domes are the most severely affected by this alteration. This work aims to delineate the spatial distribution and characterize the mineralogy of the hydrothermal alteration affecting the domes. Such information will improve the understanding of the associated hydrothermal processes at the PCVC.

Multispectral remote sensing techniques were applied using Landsat 8 OLI and Landsat 9 OLI imagery processed on the Google Earth Engine platform. Band ratios were used to highlight minerals typically associated with hydrothermal alteration, such as clays, sulfates, and iron oxides. Alteration intensity maps were generated, revealing significant spatial variations at the PCVC, with the highest alteration intensities displaying concentric zoning patterns surrounding the domes. Comparison of the remote sensing-derived maps with field and petrographic observations confirmed a strong correspondence between sensor-identified alteration zones and those encountered in the field, validating the effectiveness of this workflow.

Integrating multispectral remote sensing, field observations, and mineralogical analyses not only allows delineation of the extent and spatial variability of the hydrothermal alteration at the domes but also provides insights into the evolution of the PCVC. Furthermore, these findings establish a replicable methodology for volcanic systems elsewhere and constitute a powerful tool for understanding interactions between volcanism and hydrothermal processes, and assessing geothermal potential

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P21.6

Tephra from the Leiðólfsvell Rootless Cone Group: Implications of Sustained Rootless Eruptions

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In summer of 1783, Laki lava flowed into the Hellisá river channel near Mt. Leiðólfsvell, changing the course of the river, whilst also producing secondary explosive eruptions. This created the Leiðólfsvell rootless cone group (LRCG), 1-2 km NW of the mountain. Contact between incandescent lava and saturated sediment and soil prompted explosive lava and water interactions (i.e. of fuel coolant type) producing a group of rootless cones (RC) in the lava. This area provides a unique opportunity to assess dynamics of large, sustained rootless eruptions.

Our field campaign during summer 2025 has expanded upon the area of previous analysis at the LRCG, aiding interpretation of its eruptive history. The products of the eruptions here are exposed in a $\sim 5 \text{ km}^2$ zone within the Laki Lava flow as a cluster of 5-240 m wide spatter and scoria cones. The scoria and ramparts display typical spatter angle of repose, whilst spatter dominated slopes tend to be steeper. However, part of the cone group has been covered by younger Laki lava flows. Welding of spatter is very limited in the cones, suggesting the formation via fuel coolant interactions. These large ramparts importantly indicate that certain rootless eruptions here were more sustained than typically assumed. The explosive activity within the LRCG produced a tephra fall deposit covering $\sim 25 \text{ km}^2$ with $>0.5 \text{ cm}$ thickness. Closest to the source vents, the tephra is up to $\sim 7 \text{ m}$ thick, rapidly thinning to a mm scale visual trace over the distance of 6 km along the main dispersal axis. Field observations revealed that both the cones and proximal tephra deposits are distinctly bedded, and tephra fall features up to 7 inverse graded layers. The inverse grading suggests that large individual eruption pulses intensified over time, whilst bedding is testimony to deposition from sustained (hrs to days long) eruptions. Also, within proximal sections, a thick, very coarse-grained unit towards the top, rich in scoria-lapilli and bombs ($>5 \text{ cm}$) signifies an overall increase in eruption intensity with time. A refined LRCG tephra dispersal map features a southeasterly dispersal axis, consistent with the interpretation that these eruptions began on the 17th July 1783, when an eruption plume was dispersed from the area by a northerly wind (Steingrímsson 1783). Observed sharp west-trending thinning rates from this group align with this deduction. Preliminary tephra isopach mapping indicates total volume of $2.2 \times 10^6 \text{ m}^3$ for the LRCG tephra blanket. Further analyses of the field measurements will be undertaken to better constrain the eruption source parameters for these eruptions and the potential hazards they may pose.

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P21.7

Volcanic facies and eruptive environment of the rhomb porphyry lavas in the Permian Oslo rift

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An important constituent of the early to middle stages of the Permian Oslo rift volcanism are the trachyandesitic/latitic rhomb porphyry (RP) lavas. The RP volcanism represents the main rift stage which began around 300 Ma and lasted for 20 Myr. No vents or eruptive sites have been documented for the RP lavas which have traditionally been interpreted as the product of large sheet-flow forming effusive eruptions in an arid environment. However, no detailed volcanic facies analyses of the lava flows have been undertaken in modern times. In this study we combine field observations from newly excavated roadcuts with drill cores from the same area to identify key volcanic facies variations within the RP lava flows. Identified facies include composite lava flows with well-developed lobes through to massive, locally inflated flows. The lava tops range from simple to thick rubbly flow tops, typically associated with slabby to rubbly pahoehoe lava flow facies. The rubbly flow tops are dominated by angular autobrecciated fragments, but a significant proportion of fragments indicate a fluidal state during ballistic transport before incorporation with the autobrecciated material. Top zones are often infiltrated by fine-grained sediment, and thin (<1m) sedimentary interbeds of sand/siltstone, with or without juvenile volcanoclastic material, are common. The flow bases show limited interaction with underlying sediments; interaction is primarily limited to loading structures and minor lobes intruding into underlying altered volcanoclastic sediment. The formation of pillow-like lava lobes could indicate local interaction with water (e.g., ephemeral lakes/rivers etc.) in an otherwise arid/semiarid environment. The spectrum of facies suggests that effusive eruptions dominated. However, the identification of pyroclastic material in the flow top zones points to explosive phases of the eruptions, and potentially a proximity to the vent zone.

P21.8

Emplacement environment of the Sattasvaara komatiites, N-Finland

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The ≥ 2.05 Ga Sattasvaara komatiite volcanic formation is the uppermost unit of the Savukoski Group of the Central Lapland Greenstone Belt (CLGB), which is part of the Paleoproterozoic supracrustal rocks in the northern part of the Fennoscandian Shield (e.g., Lethonen et al. 1998). A lowest unit of the Savukoski Group is the graphite-sulphide schist of the Matarakoski formation that within a shallow anoxic ocean of an extensional basin that also featured the picritic and komatiitic lava- and volcanoclastic-producing volcanism. Saverikko (1985) demonstrated that the Sattasvaara formation consists of both lava flows and volcanoclastic deposits. Along with pillow lava and coherent lava sheets, Saverikko also identified horizons of lapillistone, lapilli tuff and tuff within the sequence. In his interpretation the Sattasvaara Hill (proper) represents a cinder cone surrounded by pyroclasts and lavas implying that the volcanoclastics were formed by explosive activity in an effusive, and presumably subaerial, komatiite eruption. Here, I present the results of detailed field mapping of the komatiite sequence exposed at the hill of Sattasvaara in North Finland, which is complemented by petrographic and geochemical analysis of a sample suite representative of the sequence. The new mapping shows that the sequence, indeed, consist of intercalated lava and volcanoclastic horizons, that appears to have been emplaced on a sloping surface close to angle of repose. The lava-bearing horizons feature either thin pahoehoe sheet lobes, stubby pahoehoe lobes or pillow lava. The volcanoclastic horizons are typified by pillow lava breccia, graded breccia to lapilli tuff, and lapilli tuff lithologies, which primarily were formed by passive (i.e., gravity-induced) breakdown of the lava lobes. Occasional lenses of planar to cross-bedded tuff horizons are present within the sequence, suggesting emplacement by wave- or gravity-induced action. Chemical analyses of these amphibolite-chlorite meta-komatiites confirm their Al-undepleted nature, relatively high TiO_2 contents, and a likely mantle plume origin of these magmas (e.g., Hanski et al. 2001). Collectively this evidence suggest that the komatiite sequence exposed at Sattasvaara Hill is part of a lava delta, formed when lava from a subaerial effusive eruption advanced from land into the sea, most likely on an ocean island.

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O22.1 (Keynote)

Platinum-group minerals and their applications

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There are currently 170 platinum-group minerals (PGM), recognized by the Commission on New Minerals, Nomenclature and Classification (CNMNC) of the International Mineralogical Association (IMA). Amongst up to date 170 known PGM, there are 82 - palladium, 38 - platinum, 24 - rhodium, 15 - iridium, 7 - ruthenium and 4 - osmium dominant PGM. The largest class of minerals are sulphides – 40, followed by tellurides - 24 and arsenides – 23, reflecting the chalcophile character of PGE. There is also a significant class of alloys - 20 reflecting the siderophile character of PGE. Regarding the type locality, most PGM were described from the localities in Russia - 65, in particular from deposits of Norilsk-Talnakh, followed by South Africa - 17, Canada - 17 and China - 15.

We have tried to synthesize the majority of PGM at the Laboratory of Experimental Mineralogy at the Czech Geological Survey. For the purpose of this study the silica-glass tube method was applied. The aim is to study in a detail the mineral properties and to advance the understanding of natural process that led to the PGM formation. A number of PGM have shown specific unique properties.

Several PGM display unique crystal structures (e.g.: sluzhenikinite, $\text{Pd}_{15}(\text{Sb}_{7-x}\text{Sn}_x)$ $3 \leq x \leq 4$; viteite, Pd_5InAs ; or thalhammerite, $\text{Pd}_9\text{Ag}_2\text{Bi}_2\text{S}_4$). Mineral monchetundraite, Pd_2NiTe_2 was predicted as a new superconductor via machine learning. Mineral jacutingaite, Pt_2HgSe_3 , has been receiving a vast attention due to its quantum spin Hall insulator (QSHI) behaviour, opening possibilities for low-power nanoscale electronic and spintronic applications. Mineral mitrofanovite (Pt_3Te_4), was proved to be a topological metal with termination-dependent surface band structure and spin polarization. One of the most common palladium minerals kotulskite (PdTe) was recently regarded as a candidate for Dirac semimetal and unconventional superconductivity (Du et al. 2025). Palladium-based chalcogenides are being an innovative class of materials extensively studied as electrocatalysts (Zhou et al. 2025).

A detailed knowledge of synthetic counterparts of PGM and experimental study may help further characterize PGM not only from mineralogical point of view (defying thermal stabilities, solid solutions, structural mechanisms of various substitutions, predicting stable assemblages) but also in terms of application in materials science and potentially in geometallurgy.

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022.2

Speciation and characterization of Pd in pentlandite from Bushveld, Lac-des-Îles, and Noril'sk ores using X-ray absorption spectroscopy

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Pentlandite (Fe,Ni)₉S₈ is one of the key host minerals of Pd in Ni and PGE deposits. However, the Pd incorporation mechanism in pentlandite is still highly disputed, leaving the question of whether Pd forms nano-sized inclusions or solid solution. We studied pentlandites exhibiting a uniform distribution of 300 – 1800 ppm of Pd from Bushveld, Lac-des-Îles, and Noril'sk ores. Pd K-edge XANES/EXAFS and Pd L₃-edge HERFD-XANES measurements were performed at BM08 and ID26 beamlines of the ESRF, respectively.

Firstly, pentlandites from Lac-des-Îles and Noril'sk ores were compared. Analysis of the Pd K-edge XANES spectra of both samples demonstrated that the formal oxidation state of Pd is close to +2. The XANES spectra simulations and EXAFS spectra fittings showed that Pd forms a solid solution. In addition, the EXAFS spectra analysis demonstrated that Pd atoms prefer to occupy the octahedral cationic sites of the pentlandite structure rather than the tetrahedral ones. Secondly, pentlandites from Noril'sk and Bushveld (UG-2 chromitite) ores were studied. Since it was established that pentlandite from Noril'sk ores contains Pd²⁺ as a solid solution, we recorded the Pd L₃-edge HERFD-XANES spectrum of this sample to obtain a 'fingerprint' of the solid solution. Comparison of the Pd L₃-edge spectra of samples from Noril'sk and Bushveld ores showed that the shapes and positions of the major peaks of the spectra are almost identical, indicating that the state of Pd is the same. Hence, we demonstrated that the pentlandites from Bushveld, Lac-des-Îles, and Noril'sk ores can contain Pd in solid solution in the octahedral sites of the structure.

O22.3

Development of characterize melt inclusion with FIB-SEM and SC-XRD

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Platinum group minerals (PGM) are often very small and difficult to examine. This study presents a new method for analysing micron-sized inclusions. Micron-sized inclusions are important links in ore genesis, ore exploration and mineral processing. Their small size often makes it impossible to measure their crystal structure. By combining different analytical instruments, field emission scanning electron microscopy (FESEM) and electron backscatter diffraction (EBSD), focused ion beam electron microscopy (FIB-SEM) and single crystal X-ray diffraction (SC-XRD), it is possible to measure the crystal structure.

EBSD is becoming an important method in geology and mineralogy. Unlike Energy Dispersive Spectrometry (EDS), which only shows the mineral composition, EBSD shows the crystal orientation of a selected sample. In this study, a JEOL JSM-7900F FESEM and Oxford instruments symmetry EBSD were used to study polished Pt-Cu nuggets. The measured Pt-Cu nugget contained several crystals, which is not an ideal sample for SC-XRD. For crystal structure measurements, the sample must be single crystal without other crystals or minerals. For the measurement, a small 20x20.20um cube of the selected crystal was prepared using FEI Helios DualBeam FIB-FESEM. The EBSD map was used to locate the single crystal. The prepared cube was transferred to a thin needle holder and measured using a Bruker D8 Venture SC-XRD.

SC-XRD work revealed that the Pt₃Cu is an ordered orthorhombic Cmmm structure of dimensions $a = 7.708$, $b = 5.4504$, $c = 2.7252$ $Z=4$. Element composition for the Pt₃Cu mineral is Pt 84,43 Cu 13,66. Orthocuproplatinum crystal structure has been previously revealed by Cabral et al. (2019). Measured data show similarities to their results, however further investigations are needed to calculate stoichiometric composition of the Pt₃Cu. Measured element composition is more favourable for Pt₂Cu.

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O22.4

Determining surface exposure of sulfides in coarse gangue particles by 3D μ CT

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It is generally known that the recovery in froth flotation is a function of particle size. The recovery of mineral particles by size follows the known “elephant curve”, showing that the recovery in flotation works most effectively between 30 to 150 μ m particle size for base metals.

However, floating coarse particles has significant technical, economic and sustainability benefits. Coarse particle flotation reduces energy consumption in the grinding circuit and can increase throughput through the comminution stage. In addition, the recovery of the coarse sized tailings becomes more practical. Previous coarse particle flotation technology has utilized fluidization as a core concept. Metso has now developed a new flotation device in which coarse particles as large as 1 mm can be recovered in addition to traditional flotation sized particles without the use of fluidized beds, using froth feeding principle.

The main objective of the μ CT measurements was to determine in 3D the smallest free surface area required to recover the valuable minerals with the new Metso CPF device. Here we describe the developed μ CT workflow to measure the surface exposure of coarse sulfide-bearing particles from the products of CPF flotation test work from a porphyry copper ore. Based on the measurements, even the minimal amount of exposure of sulfides in a coarse particle is enough to recover those, going as low as 1% surface area exposure.

022.5

Characterizing Jadarite as a European Lithium Resource

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Lithium is critical for the European Union's green transition plans, supporting electric mobility, renewable energy storage, and grid-scale backup solutions. However, domestic production from both European deposits and battery-grade chemicals remains limited. Conventional European sources face additional challenges: spodumene deposits are relatively small, petalite is mainly directed to glass and ceramic industries, and lithium-bearing micas are low-grade and chemically complex. Consequently, much of the battery-grade lithium chemicals, as well as spodumene concentrates, used in EU countries with battery manufacturing capacity is still imported from China and other non-EU suppliers. Processing these minerals also requires intensive crushing and high-temperature treatment, increasing carbon emissions per unit of lithium carbonate equivalent (LCE).

In contrast, jadarite, a lithium sodium borosilicate found exclusively in a large deposit in Jadar, Serbia, could supply a significant share of Europe's lithium demand. Its distinctive mineralogy facilitates lithium-boron extraction, and mineralogical investigations indicate that optimized processing routes could also reduce carbon emissions per unit of LCE compared with conventional lithium minerals. While extraction involves local permitting, environmental, and policy-related challenges, the Jadar deposit remains one of the largest potential lithium-boron resources within Europe, offering substantial processing advantages.

Jadarite's characteristics highlight how mineralogical insights can enhance operational efficiency, environmental performance, and supply chain resilience, strengthening Europe's strategic autonomy in lithium supply. With potential multi-decade production of tens of thousands of tonnes of LCE per year, the Jadar deposit could become one of Europe's most stable lithium sources during the critical phase of the green transition. Its scale would also make it a strategic reserve for the EU, capable of supplying a significant share of regional demand over the coming years.

022.6

The Decisive Role of Mineralogy in Clean Energy Transitions

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According to the International Energy Agency's landmark report on the role of critical minerals in clean energy transitions the demand for lithium is expected to increase 42 times in less than 20 years to meet the stringent sustainable development scenario, while according to the European Commission, global lithium demand will grow almost 90 times by 2050 (IEA 2021).

The EU-funded LITHOS project is focused on the domestic processing and refining of lithium to contribute to the CRMA benchmarks. LITHOS processes ores to produce battery-grade LiOH·H₂O, expanding and customizing the existing flowsheet to increase lithium reserves and commercialize lower-grade deposits. LITHOS focuses on the three strategic hard rock lithium projects: 1) Keliber's spodumene ore from Kaustinen, Finland, 2) Savannah's spodumene and petalite ores from Barroso, Portugal and 3) Imerys' lepidolite ore from Beauvoir, France (Petrakis et al. 2025).

Even though the main mineralogy of the lithium–cesium–tantalum (LCT)-pegmatites and rare metal granites (RMG) is straightforward, the mineralogy of lithium in the ores is complex. Here we present the results of chemical and mineralogical characterization of different lithium ores and preliminary mineralogical and metallurgical findings of the on-going beneficiation test work. The test work has shown that understanding the mineralogy is a decisive key component of the flowsheet development to efficiently recover different lithium minerals.

Acknowledgements

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P22.1

The role of mineralogy in understanding the Sokli carbonatite complex and its resource potential

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Situated in northeastern Finland, Sokli ranks among the largest known carbonatite complexes globally and hosts significant multi-metal deposits. In the centre of the pipe-like complex is a magmatic core comprised mostly of carbonatite and phoscorite, which transition into metasomatised carbonatite and ultramafic rocks towards the outer zone of the complex. They are surrounded by an extensive fenite aureole, and the whole complex is cut by lamprophyre dykes of varying ages as well as late REE-bearing carbonatite dykes. Above the bedrock, layers of weathered rock, laterite, and glacial till are present. The variety of different rock types and supergene weathering products means that the mineralogical diversity encountered in Sokli is tremendous.

The lateritic phosphate deposits are mainly composed of primary fluorapatite, micas, and magnetite, with supergene francolite, crandallite, and iron- and manganese oxides. In some areas, the laterite can be enriched in REEs and Nb, where REEs are mainly incorporated into fluorapatite and monazite/rhabdophane, whereas the bulk of Nb is in pyrochlore. Laterite units enriched in Fe, Mn, and vermiculite are also found.

Sokli's most prospective hard rock mineralisation is associated with phoscorite as well as late-stage REE-enriched carbonatite. Phoscorites are potential targets for several different elements that are incorporated mainly in fluorapatite (P, REE), pyrochlore (Nb, Ta, REE, U, Th), and magnetite (Fe). The late REE-bearing carbonatite dykes comprise a highly potential exploration target, with REEs incorporated largely in kukharenkoite as well as ancylite and monazite. Additionally, the whole carbonatite massif can be considered as a giant low-grade phosphate resource with approximately 3.5 wt.% of P₂O₅.

Due to the wide array of minerals encountered in Sokli, mineralogical studies are a central part of Sokli Oy's operations. Methods, such as hyperspectral-, micro-X-ray fluorescence- (μXRF), and laser-induced breakdown spectroscopy (LIBS) scanning have been utilised. High-throughput synchrotron X-ray powder diffraction (HT-SR-XRPD) and scanning electron microscopy (SEM) are also some of the many methods that have been used. The results have improved, for instance, the quality of drill core logging and geological modelling. They will also be crucial for any geometallurgical modelling as well as possible pilot beneficiation plant operations.

Mineralogical studies will continue to be the backbone of operational advancement and scientific research in Sokli. With growing demand for elements like REEs, P, Nb, and Mn, Sokli stands out as one of Europe's most strategically important deposits of critical raw materials.

023.1

Age and structural history of the Paleoproterozoic A-type Puula granite in the core of Fennoscandia – implications for the evolution of the Svecofennian orogen at 1.88–1.87 Ga.

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We have studied the evolution and structural history of the Paleoproterozoic A-type Puula granite to understand the effects of far-field tectonic events on apparently undeformed to slightly deformed post-kinematic granites in the core of the Svecofennian orogen. The Puula granite is divided into three different magma types: 1) Magma dominated by abundant xenoliths and characterized by small K-feldspar phenocrysts (< 30 mm). 2) Dominant magma type depicted by intermediate size K-feldspar phenocrysts (35–40 mm) and lack of abundant country-rock xenoliths. 3) Feeder zone magmatism exemplified by crystal mush, including megacrystic and often anhedral K-feldspar phenocrysts (> 45 mm), the occurrences of complex overgrowth structures and abundant felsic to intermediate aplitic to fine-grained granite sills/dykes. Based on age data the emplacement duration of the Puula granite is probably from ca. 1880–1878 Ma to 1875 Ma. Structural evolution of the Puula granite started with sub-horizontal NW-vergent stacking ($D_{\text{oroclinal}}$; 1875–1865 Ma) followed by major NE–SW shortening (D3; 1865–1850 Ma) and subsequent minor NW–SE shortening (D4; 1840–1800 Ma). All these events are far field in nature and occur in the outboards of the core of the Svecofennian orogen. The Puula granite is also characterized by abundant rock scarps and exfoliation joints formed along older planes of weakness.

We propose that the Puula granite and comparable Suontee and Joutsa granites have originally been part of a zoned Puula batholith, at least 100 km by 60 km in size, later deformed (mainly during D3) into three separate granite units. The Puula batholith is an example of A-type 1880–1875 Ma magmatism characteristic for the Central Finland Granitoid Complex. Coeval volcanic and sedimentary rocks are found from Skellefte in Sweden to central and southern Finland, which are all modeled to have formed during an extensional stage within back-arc setting. Three scenarios proposed for the tectonic evolution of the Svecofennian orogen at 1.89(1.88)–1.87 Ga are compared. In the favored model linear arc magmatism (1905–1885 Ma), subsequent collision/accretion (1885–1880 Ma) and a short large-scale extension period (1880–1875 Ma) was followed by oroclinal buckling and shortening (1875–1865 Ma). Solely accretionary models discuss single or few arc segments, but a fragmented single linear arc is also advocated. The collisional model includes separate arcs of the same age with several subduction zones, and contemporaneous extension and shortening at 1880–1870 Ma.

O23.2

Extensional 1.88–1.85 Ga mafic magmatism in Southern Finland as part of the larger Fennoscandian tectonic puzzle

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Roughly 1870–1850 Ma mafic dykes and plutons that crosscut earlier lithologies in the 1.9–1.8 Ga Southern Finland Subprovince (SFS) have traditionally been called “intraorogenic” (Sederholm 1926; Simonen 1980). Recent studies indicate that many of these mafic rocks show MORB-like geochemical affinities that imply extensional tectonics (Kara et al. 2021; Johnson et al. 2025).

Hermansson et al. (2008) suggested that tectonic switching (alternating contraction and extension due to a retreating and advancing slab) could be the cause for back-arc magmas in the Swedish part of the Svecofennian domain. On the Finnish side, Kara et al. (2021) presented a model where subduction towards today’s north produces alternating arc-type and extension-type magmas intruding the northern part of SFS periodically between 1920 and 1860 Ma.

Our recent observations from the SFS (Uusimaa belt) give additional information about the timing of the extension. U-Pb (zrn) dating of gabbros in the central part of the SFS yielded an age of ca 1860 Ma, while further south in the archipelago of the Gulf of Finland, metabasaltic dykes span ca 1878–1867 Ma in age. Geochemically, the older dyke rocks are more enriched (E-MORB affinity) likely due to a deeper magma source and/or crustal involvement during incipient rifting, whereas the more northern gabbros resemble slightly more mature back-arc magmas with E-MORB to N-MORB geochemical affinities.

The new data indicate that the whole SFS has been affected by tectonic switching while the continental margin with constant polarity gradually retreated further towards (today’s) southwest. Though the process is sweeping over the SFS fairly linearly in time and space, local differences in both age and geochemistry are due to differences in the extent of strain, lateral extension and inherited zones of crustal weakness.

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023.3

Geochemical constraints on the generation of simple pegmatites in the Ostrobothnian Schist Belt, western Finland

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Global demand for critical elements for high-technology industries is rising rapidly. As a consequence, pegmatite research has also increased, as up to 60 % of critical elements (e.g., Li, Ce, Ta, Nb, Sn) are mined from the spodumene-bearing pegmatites. As research focuses on pegmatites associated with Li occurrences, research on non-mineralized simple pegmatites may be left behind. The Ostrobothnian Schist Belt (OSB), in western Finland, gives a chance to also study such simple pegmatites, which occur in close spatial contact with the more evolved albite-spodumene pegmatites (Mäkitie et al. 2001). To understand the genesis of evolved pegmatites, the genesis of simple pegmatites must also be understood.

This study concentrates on the whole-rock geochemistry of the andalusite/sillimanite metapelite country rocks from the OSB as well as cross-cutting muscovite-tourmaline-garnet pegmatites. The simple leucogranitic pegmatites are “post-orogenic” (formed at the end of the Svecofennian orogeny at ~ 1.79 Ga ago; Alviola et al. 2001). They intruded the upper crust, reflecting craton-wide, mid-crustal melting events in the lead-up to final cratonization. In the OSB, pegmatites and leucogranites represent the only felsic magmatism contemporaneous with the Li-rich pegmatites, but their genetic relationships are unclear. This study, with the presented whole-rock geochemical analyses and geochemical modelling, fills that gap.

The whole-rock geochemistry of pegmatites was compared to results of experimental partial melting studies to pinpoint that similar peraluminous leucogranitic melts as pegmatites can be generated by simply melting the OSB metapelites. The trace element content of pegmatites was then compared to results of modeling using recently published partition coefficients for strongly peraluminous leucogranitic melts (Pichavant et al. 2024). This study shows that low-degree melting of metapelites with subsequent fractional crystallization is a viable model for simple pegmatite generation in the OSB.

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O23.4

A proposed Paleoproterozoic core complex in the Ljusdal lithotectonic unit, central Sweden

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Core complexes are typically formed in extensional settings often accompanied by partial melting, emplacement of granitoids and crustal-scale, low and high angle deformation zones (e.g., Joliver et al. 2021). Of these, migmatite-cored metamorphic core complexes are associated with formation of voluminous syn-kinematic partial melts that facilitate crustal flow and buoyant rise of rocks and melt from the lower parts of the crust. Formation of the principal rocks of the Ljusdal lithotectonic unit seem to be in accordance with this description.

The Swedish part of the Paleoproterozoic Svecokarelian orogen is divided into six lithotectonic units, of which most are separated by major plastic shear zone systems. The Ljusdal lithotectonic unit in the central part of the orogen is delimited to the north by the Hassela Shear Zone (HSZ) and by the Storsjön-Edsbyn Deformation Zone and the Hagsta Gneiss Zone to the west and south. It is dominated by the Ljusdal batholith with zircon crystallisation ages between 1870 and 1843 Ma. Coarse-grained granodiorites are the most common rock within the batholith with minor components ranging in composition from granitic to ultramafic. Subsequent metamorphism occurred at c. 1.86 (M1) and 1.83 Ga (M2). Scattered metasupracrustal inliers are present within the batholith that in turn is flanked by 1.86 Ga diatexites with associated leucogranites. The proto-HSZ coincides with a steep 1.86 Ga diatexite belt with documented syn-migmatite dextral shear. To the east of the batholith the diatexites are occasionally orthopyroxene-bearing and the PT-condition during M1 has been calculated to 0.2-0.35 GPa and 740-770°C. Wide deformation zones within these diatexites have a strong planar fabric with a moderate easterly dip often followed by a well-defined stretching lineation. Asymmetric folds within the deformation zones show top-to-the-west kinematic, but they may have been established originally as extensional structures. They could thus represent detachments above the plutonic rocks of the batholith, which suggests that proto-HSZ behaved as a transfer structure and that the rocks of the batholith were emplaced in a metamorphic core complex in an overall extensional environment. A positive gravity anomaly in the central part of the batholith may represent co-magmatic mafic rocks that acted as the heat source producing the felsic melt that raised through the LP-HT dome aided by extensional, crustal-scale shear zones later reactivated in a reverse sense during M2. Similar concomitant core complexed displaying a cooling gradient in the surrounding migmatites away from the central parts of the core are the Vaasa Migmatitic Complex in Finland and the Albacken intrusion to the NW of Ljusdal batholith.

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023.5

The active Fennoscandian margin in Geon 16

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The main part of the 1.7-1.6 Ga Fennoscandian bedrock has been displaced and reworked during the 1.5-1.4 Ga Hallandian, the 1.1-0.9 Ga Sveconorwegian, and the 0.5-0.4 Ga Caledonian orogenies. It is also partly covered by Phanerozoic sedimentary rocks. As a result, the geological setting of the active Fennoscandian margin in Geon 16 is poorly understood and often foreseen in models of the orogenic evolution of the continent.

Subduction along a progressively thickened Fennoscandian margin in the late Paleoproterozoic resulted in extensive alkali-calcic magmatism forming the western coherent part of the Transscandinavian Igneous Belt (TIB), increasing in volume, and decreasing in age towards the active continental margin. In the shield, TIB magmatism is recorded in three intervals at 1.87-1.84 Ga, 1.81-1.77 Ga, and 1.74-1.66 Ga. However, TIB rocks also constitutes a major part of the Caledonides including the parautochthonous basement, the basement nappe sheets, and the autochthon beneath the nappe complex. Igneous emplacement of TIB rocks in the east-central Caledonides is dated at 1.69-1.63 Ga and this part of the TIB is thus partly considerably younger than the TIB in the shield (Andersson et al. 2022). Together with 1.69-1.62 Ga TIB rocks in the Western Gneiss Region (Slagstad et al. 2024) and in the basement nappes in the south-eastern Caledonides (Lamminen et al. 2011), they are the remains of a large-scale magmatic province formed along the active Fennoscandian margin at 1.69-1.62 Ga with a pre-Caledonian extent to the west-north-west following the inferred nappe transport direction. The extent of TIB rocks formed in the 16 Geon is even more extensive if accepting models where 1.74-1.66 Ga TIB rocks of the Eastern Segment of the Sveconorwegian orogen is underlying the western allochthonous Sveconorwegian orogenic segments (Sveconorwegia), west of the Mylonite Zone in the present-day southern Norway. Regardless of the latter, the 1.74-1.62 Ga TIB formed an extensive accretionary orogenic system along the active Fennoscandian margin to be accounted for in models of the orogenic evolution of Fennoscandia and in correlations of orogenic events in other continents.

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O23.6

Bedrock mapping in Kristiansand and Nissedal, S Norway, leads to simpler collisional model for the Sveconorwegian orogeny

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Bedrock mapping in the Kristiansand (2020-2025) and Nissedal (2017-2022) areas provides new field, geochemical, and geochronological data on the Telemark and Bamble Lithotectonic Units (LU), Sveconorwegian Orogen. Zircon U-Pb data were generated in 84 (meta)magmatic and 11 metasedimentary rocks, zircon Lu-Hf data in 45 of them, and monazite U-Th-Pb data in 11 metasedimentary rocks.

The Kristiansand area overlaps the Bamble and Telemark LU, across the Kristiansand-Porsgrunn shear zone. The oldest magmatic rocks, commonly tonalitic, range from 1555 to 1500 Ma in both units. On the Bamble LU side, metasedimentary packages contain sulfide-bearing layers. The diorite-monzonite-granite 1340-1325 Ma Frikstad suite is a new discovery, coeval with the Kungsbacka suite in the Idefjorden LU. On the Telemark LU side, the quartzite-greywacke Ålefjær metasupracrustal complex correlates with the quartzite-dominated Seljord sequence. Granitoids at 1280-1250 and 1155-1140 Ma are part of known bimodal magmatic suites. Thin high-K-Sr-Ba alkali monzonite plutons at 1040 Ma are coeval with the high-K calc-alkali plutonism westwards and lamprophyre eastwards. They have typical syn-collisional slab-failure geochemistry. In addition to the known amphibolite-facies metamorphism at 1050-1000 and 950-930 Ma, data importantly uncover a metamorphic event at 1150-1130 Ma on the Telemark side, so far exclusively reported in Bamble and Kongsberg. On the Bamble side metamorphism is dated at 1320-1300 and 1150-1120 Ma, with no evidence for younger events. The data suggest that the 1150-1130 Ma metamorphism is intrinsically driven by magmatism, and that the Bamble and Kongsberg LU were exhumed by thrusting along the Kristiansand-Porsgrunn shear zone before c.1050 Ma.

The Nissedal supracrustal complex in Telemark is dominated by subalkali 1200-1180 Ma metabasalt and metarhyolite. The structurally underlying Vråvatn gneiss complex consists of 1230-1180 Ma A-type metagranite. Elevated (up to 9) epsilon Hf(i) values imply a depleted mantle component. Metamorphism in metasediment units is coeval with this magmatism. Quartzite boulders in metaconglomerate layers are sourced in the older Seljord sequence. The Nissedal supracrustal complex is interpreted as a magma-rich within-plate continental rift sequence.

The Kalhovde siliciclastic formation was redated and shown to be younger than c.1130 Ma (rather than c.1050 Ma). It is re-interpreted as one of the post-1130 Ma non-magmatic intramontane basins. No post-1060 Ma sediment basin is positively identified inside the Sveconorwegian Orogen.

Two geodynamic models prevail for the Sveconorwegian orogeny: collisional vs. accretionary. We re-evaluate and simplify the collisional model. The 1340-1060 Ma evolution corresponds to hot magma-rich (1340-1130 Ma) then non-magmatic (1130-1060 Ma) continental rifting. Collision started at c. 1060 Ma, involving slab failure and eastwards retro-delamination of the lithospheric mantle.

P23.1

Timing of magmatic-hydrothermal events at the Järkvissle Li-Sn-Ta pegmatite deposit, Sweden: Constraints from cassiterite and apatite U-Pb LA-ICP-MS geochronology

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The Järkvissle Li-Sn-Ta pegmatite deposit occurs in Västernorrland County in central Sweden. The deposit consists of a c. 2 x 7 km, N-S-trending field of subparallel, LCT-type and simple pegmatites that intrude a package of Paleoproterozoic metasupracrustal rocks (e.g. Lynch et al. 2023). Previous columbite U-Pb ID-TIMS dating at Järkvissle indicates pegmatite emplacement occurred at c. 1800 Ma during a late- to post-orogenic stage (Romer & Smeds 1997). We present new cassiterite and apatite U-Pb LA-ICP-MS dating results for a spodumene-bearing pegmatite sample (ELH220032A) from Järkvissle that affirms the timing of LCT pegmatite emplacement at c. 1.80 Ga and identifies a younger, overprinting hydrothermal event at c. 1.52 Ga. The research forms part of the Horizon 2020 *Exploration Information System (EIS)* project (grant no. 1010557357) and SGU *Västernorrland Li* project.

U-Pb LA-ICP-MS analysis was conducted at GEUS and followed the methodology described in Keulen et al. (in press). Subhedral cassiterite with internal zoning yielded a lower intercept U-Pb date of 1806 ± 16 Ma ($\pm 2\sigma$, $n = 13$, optimised to MSWD = 1.6). The new date is the same within uncertainty as the earlier acquired columbite U-Pb upper intercept date of $1800 \text{ Ma} \pm 4 \text{ Ma}$ (Romer & Smeds 1997). The combined results affirm an LCT pegmatite emplacement event at 1.81 – 1.80 Ga. Analysis of interstitial apatite produced a lower intercept U-Pb date of 1521 ± 21 Ma ($\pm 2\sigma$, $n = 29$, optimised to MSWD = 2.2) which, although statistically less robust, marks a younger overprinting hydrothermal event associated with the isotopic resetting of earlier-formed apatite.

The new cassiterite and apatite U-Pb dates record two temporally distinct Proterozoic tectonothermal events at Järkvissle. The cassiterite date (c. 1806 Ma) links LCT pegmatite formation to a recognised Li ± Sn ± Ta ± Cs metallogenic window active in central Fennoscandia from c. 1.81 – 1.78 Ga during the later stages of the Svecokarelian orogeny. In contrast, the younger apatite date (c. 1521 Ma) suggests a phase of post-emplacement modification recorded by the hydrothermal resetting of apatite. This latter event is documented by other U-Pb and Rb-Sr age signatures between c. 1.6 – 1.5 Ga from across Sweden, and may reflect far-field tectonothermal events that affected the margins of the Paleoproterozoic orogenic domain after 1.7 Ga.

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P23.2

Two unrelated volcanic sequences in the Fröderyd group?

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The Fröderyd group in southeast Sweden mainly comprises basalts of MORB affinity (Sundblad et al. 1997). The basalts are locally well-preserved and pillow lavas are common, and suggests younging towards the northwest. The group also contains felsic volcanic units (quartz porphyries), but the relationship between these contrasting rock types is not entirely clear. The volcanic sequence has an age of 1.85 Ga (Salin et al. 2021), c. 15–30 m.y. older than the bordering Oskarshamn-Jönköping belt.

Mapping in the northwest has revealed a volcanic sequence not seen in the Fröderyd group before – a layered series of mostly felsic pyroclastic material, from fine-grained and finely laminated beds to homogenous decimeter-thick layers with coarse sand-sized clasts. The coarser layers sometimes carry pebble-sized rock fragments and occasional larger amphibolite clasts. In places the finely laminated and coarse-grained beds interchange rhythmically with individual bed thicknesses of 1–2 dm. Sparsely occurring cross-bedding suggests younging towards the southeast, i.e. opposite to the basaltic units. Local folding is common in the sequence, which could suggest slumping or other secondary sedimentary processes. The layered and laminated sequence is further deformed and folded in a way not seen in the main part of the group, and the mineral assembly suggests a higher metamorphic grade. Field relationships show that the sequence is older than intrusive rocks of the Oskarshamn-Jönköping Belt, but the age of the layered sequence and the relationship to the main part of the Fröderyd group are so far unknown.

If the layered sequence is related to the basalts, two scenarios are possible – either the layered felsic sequence marks the initial stage of the Fröderyd group formation, i.e. early rifting in an older volcanic arc (e.g. the "Nömmen volcanic arc" of Salin et al. 2021). The second scenario is that the layered sequence formed late by crustal melts initiated by the basaltic magmatism, and could then also be related to the quartz porphyries that are more common in the northwest. There is also a possibility that the layered pyroclastic sequence is unrelated to the rest of the Fröderyd group. Whole-rock geochemistry and petrographic and chemical analyses of magmatic and metamorphic minerals in both the layered sequence and rocks of the main Fröderyd group will hopefully yield further clues to the origin of this still enigmatic volcanic sequence.

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O24.1 (Keynote)

Linkage between seismic deformation, strain softening and volume expanding hydration and carbonation reactions in peridotites from the Reinfjord lower crustal field laboratory

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The response of peridotites to infiltrating H₂O-CO₂ fluids depends on primary mineralogy, affecting fluid flow through the lower crust and upper mantle, as mineral reactions control permeability and rheology. Samples are from the hanging wall of a 2 km-long transtensional shear zone within peridotites in the Reinfjord Ultramafic Complex (RUC), part of the Seiland Igneous Province (SIP).

Fluid-rock interaction around shear zones with pseudotachylytes varies and depends on bulk rock compositions. Thermodynamic modelling shows mineral reactions involving hydration and carbonation differ between dunitic rocks and the intersecting pyroxenitic dykes. Dunitic alteration yields magnesite-anthophyllite-talc assemblages, causing approximately 12% volume expansion, resulting in a sharp contact with the host rock. When crossing the dunite-pyroxenite boundary, alteration becomes more gradual, widening by about 40%. Pyroxenites are altered to complex mixes of cummingtonite-anthophyllite, magnetite, chlorite, with orthopyroxene pseudomorphed by cummingtonite and magnetite, and partly preserved olivine surrounded by magnesite and anthophyllite. Cavities are filled with chlorite, amphibole, and Mg-Ca carbonates, indicating volume reduction during pyroxene alteration. Ni, Cu, and minor Zn sulfide mineralization is associated with hydrothermal infiltration.

Dunite alteration effectuates a significant volume expansion and are therefore only altered locally during seismic creep events whereas the pyroxenites are near neutral volume and homogeneously altered. The formation of chlorite in hybrid compositions, such as the dykes in the lower crust, may create weak permeable zones that are consequently exploited as pathways for fertile mantle fluids and will hence also be the locus of ore bearing fluids moving to the upper crust. The hydrothermal assemblages are closely related to seismic deformation (pseudotachylytes) caused by local strain softening due to carbonation of olivine and clinopyroxene to form orthopyroxene and dolomite in the peridotites (Sørensen et al. 2019), commonly associated with volatile rich mafic dykes (Ryan et al. 2022). Either the ductile magnesite-chlorite-talc assemblages formed at the same time in a shear-related heat gradient, or they formed during cooling and continued CO₂ infiltration from depth through the shear zones.

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O24.2

Importance of juvenile volatiles in intracrustal emplacement of LIP melts and the formation and disruption of Cu-Ni-PGE deposits

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We propose that the Seiland Igneous Province (SIP) in N. Norway represents an easily accessible epitome of a Lower Crustal Body (LCB) predominantly featuring mafic-ultramafic mantle-derived plutons. The 5000 km² SIP emplaced into gneissic basement rocks at depths of 0.6-1 GPa at a magma-rich passive volcanic margin.

SIP formed at Ma 570-560 and is associated with a LIP known as the Central Iapetus Magmatic Province (CIMP). Our studies show that the emplacement of nominally dense juvenile melts is enforced by unexpectedly high volatile contents, which are buffered by immiscible H₂O-CO₂-rich alkaline silicate melts.

Four large peridotite complexes feature the main conduit systems for the inter-crustal emplacement of thousands of km³ of basic and ultrabasic melts. Gravimetric studies show that the ultramafic conduits are extending >9 km downwards. These ultramafic conduits are well exposed in a right-way-up position in steep-walled 20-200 km² plugs. From edge to core, they comprise a marginal hybrid zone towards the country rock, followed by olivine-clino-pyroxenite cumulates, then wehrlitic and, at the centre, dunitic cumulates. Parental melt modelling implies ultramafic fertile parent melts with 16–22 wt.% MgO, 1594 ppm Cr and 611 ppm Ni. They were emplaced at 1400–1500°C and mostly formed at 1630°C at 7 GPa by partial melting of carbonated asthenospheric peridotite. Abundant hornblendites, carbonatites and lamprophyres throughout SIP confirm the volatile-rich nature of the mantle source region and are further corroborated by high contents of magmatic sulphides (0.5–1%), as well as carbonated and hydrous phases (1-5%). Volatile-rich phases are particularly common at PGE-Cu-Ni reefs where they co-exist with the ore-forming sulphide-rich assemblages. We hypothesise that immiscible volatile-rich alkaline melts aided in both deposition and later disruption of ore-deposits. Volatile phases will also lower melt densities and viscosities and may be important for rapid fluxing from the mantle throughout the deep crust to the more shallow crust and the surface realm of basic-ultrabasic melts.

In 4 exploratory drill holes we observe 5-20 metres of dunite with 0.4 wt% sulphide-bound Ni, 0.14 wt% Cu and 70 ppb PGE+Au. Tens of meters below, several 1m thick PGE reefs occur. Typically, they are grading 1-1.7 ppm PGE+Au. Example grades feature 0.8 g/t Pd, 0.4 g/t Pt, 0.2 g/t Au and, 0.3 ppb Os-rich IPGE. Variations over this theme with strong decoupling of PGE from Cu and Ni-rich horizons occur in all four drill holes, and most of the mineralised horizons are associated with narrow Cr-rich segments of the igneous stratigraphy interpreted to mark melt recharge events. We suggest that the PGE-rich reefs are formed when Cu-Ni phases were selectively remobilised during recharge events. The PGE-Cu-Ni rich zones typically occur in parasitic side chambers butting from the ultramafic conduit system and, tentatively, are suggested as the primary exploration targets.

O24.3

Nickel in mafic and ultramafic systems

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Nickel (Ni) occurs as a minor component of silicates, most notably in olivine, and as a major component in the mineral structure of Ni-Fe sulphides and Ni-oxides. Nickel partitions between silicate and sulphide minerals in ultramafic magmatic systems, where olivine scavenges Ni until conditions of sulphide saturation are met, subsequently sulphides take over as the dominant host of Ni. Laterites form during weathering of ultramafic assemblages, often in peridotite massifs, where tropical climate conditions enhance weathering. Nickel is released from olivine during alteration and concentrates in Ni-oxides associated with laterite horizons.

How do Ni isotopic compositions, combined with characteristic geochemical tracers, compare between ocean island basalts, magmatic Ni sulphide ores and Ni laterite deposits? What insights do these variations provide into Ni source characterisation and the processes of fractionation in mafic and ultramafic systems?

Ocean islands exhibit $\delta^{60}\text{Ni}$ values of -0.16 to +0.29‰, compared to Mid ocean ridge basalts with $\delta^{60}\text{Ni}$ of -0.04 to +0.24 ‰ and mantle lithologies with $\delta^{60}\text{Ni}$ of -0.08 to +0.42‰. In comparison, magmatic Ni-Cu sulphide deposits have $\delta^{60}\text{Ni}$ values of -1.69 to +0.58‰ and Ni laterite deposits display $\delta^{60}\text{Ni}$ of -0.61 to +0.9‰. We will evaluate the similarities and differences in geochemistry between these contrasting geological settings and explore the processes and factors controlling the behaviour of Ni.

O24.4

Re-Os isotope systematics of Archean and Paleoproterozoic mafic-ultramafic Ni-Cu-PGE deposits in Finland: implications to magmatic and metamorphic histories

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This study compiles Re-Os isotope data from Finnish mafic-ultramafic rocks and Ni-Cu-PGE deposits, including Archean Ruossakero, Vaara, Tainiovaara, Tulppio, and Paleoproterozoic Sakatti, Kevitsa, Lomalampi and Värriöjoki. These deposits reveal diverse magmatic origins, mantle sources, and post-emplacement histories.

Re-Os isotopes from Ruossakero, Tainiovaara, Vaara and Tulppio confirm Archean komatiitic magmatism. Vaara chromites yield a Re-Os age of 2719 ± 140 Ma with near-chondritic γ Os, despite sulfur isotope evidence for contamination. Tainiovaara shows elevated γ Os (+13), suggesting crustal input from deeper sources. Ruossakero has Re-Os age of ~ 2.9 Ga, indicating older komatiitic magmatism than elsewhere in Finland (Moilanen et al. 2019).

The Sakatti deposit yielded a Re-Os isochron age of 2063 ± 35 Ma. Chromite and olivine retain mantle-like γ Os in Sakatti, while sulfides show radiogenic Os isotope values (γ Os +21 to +56, average +33), indicating post-chromite sulfide saturation and contamination (Moilanen et al. 2021). Lomalampi chromites have Re-Os age of 2058 ± 93 Ma, with one sample indicating moderate contamination (γ Os +24) (Moilanen et al. 2019). For the Värriö ultramafic complex, the Re-Os data of chromite yield an average model age of 2100 ± 126 Ma and initial γ Os of -0.3 ± 0.7 (at 2056 Ma) (Heller 2020).

Across all deposits, chromite proves to be a robust phase for preserving primary Re-Os isotope compositions, often yielding near-chondritic initial ratios. Sulfide phases, however, frequently exhibit open-system behavior, contamination and isotopic resetting, particularly during the Svecofennian orogeny. The variation in γ Os values among sulfides reflects differing degrees of crustal contamination and timing of sulfide saturation relative to chromite crystallization.

This compilation highlights the utility of Re-Os systematics in distinguishing primary magmatic processes from secondary metamorphic overprints and underscores the complex interplay between mantle-derived mafic-ultramafic magmatism and crustal assimilation in the genesis of Ni-Cu-PGE sulfide deposits. In addition, a Re-Os isotope database of chromite is combined in CLGB, which can be used as a reference to roughly distinguish different generations of mafic-ultramafic magmatism from Archean to Paleoproterozoic of unknown samples.

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O24.5

Magma source and lithospheric control on the magmatism and orthomagmatic deposits

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Orthomagmatic ore deposits host important (critical) raw materials. In NE Fennoscandia, multiple generations of mafic-ultramafic magmatism occurred in the Paleoproterozoic rifting stage from 2.5 Ga to 1.95 Ga, forming a number of mineral deposits.

One important feature is the spatial distribution of magmatism showing intensive occurrence of layered intrusions at the boundary between Archean basement rocks and Paleoproterozoic supracrustal belts. From previous seismic data, much more intensive mafic rocks have occurred beneath the supracrustal basin, indicating more magma supply beneath these basins. Regional-scale deep penetration geophysical data show that the large layered intrusions occur at the boundary between Archean terranes and younger Paleoproterozoic terranes which have different lithospheric thickness, further indicating the critical role of lithosphere in controlling magmatism. One factor is the source of magma and metals in large igneous provinces (LIP), which is still controversial. Based on bulk rock isotope and trace elemental geochemistry and thermodynamic modelling of 2.45 Ga plume-related magmatism in Fennoscandia, the magma is derived from a mantle plume rather than a mestasomatized sub-continental lithospheric mantle (SCLM). A Re-Os isotope database of LIPs with ages spanning from Archean to Paleozoic in a global scale show that almost all LIPs have chondritic or slightly positive gOs, clearly different from typical Os isotope composition of SCLM with negative gOs. These data indicates insignificant contribution of the SCLM to both magma and metals. The implication is that the thickness of continental lithosphere may be a potential proxy for guiding regional exploration, such that the thinning of lithosphere in craton margin may be more favorable for orthomagmatic deposits.

Another important feature of orthomagmatic ore deposits in NE Fennoscandia is the dominance of large layered intrusions hosted deposits in early rifting stage, and conduit type Ni-Cu sulfide deposits in late rifting stage. On the other hand, the magmatism in middle rifting stage is generally barren. Whole rock geochemistry of coeval volcanic rocks show that magmatism in the whole rifting stage are fertile in terms of metals. However, the nature of sulfide saturation is quite different at different stages of rifting. We propose that the evolution of lithospheric structure may have played a role in controlling mineralization. Large layered intrusions related mineralization may have formed in early rifting stage, but not in middle and late stages due to weaker lithospheric strength and thus lower capability for forming large magma chambers. On the other hand, the availability of sedimentary sulfur only in late rifting stage in deepened basin may controlled the formation of Ni-Cu sulfide deposit. This is supported by precise Re-Os dating of black shales (2.13 Ga) in Central Lapland Belt, which is slightly older than main ore formation period of 2.06 Ga.

P24.1

Understanding the regional structural framework and controls on Ni-Cu-Co mineralization, in the Ringerike Magmatic Belt, Norway

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The Ni-Cu-Co mineralization in the Ringerike Municipality, Norway, is associated with a suite of magmatic intrusions occurring within the Eastern Kongsberg Complex (EKC). The complex formed during the Gothian Orogeny (1.6 - 1.5 Ga), and the most significant local Ni-Cu deposits are predominantly correlated with this magmatism (Orvik et al. 2025). Historically, nickel and copper were produced in this area until operations ceased in 1920 (Mathiesen & NGU 1977).

In recent years, both industry and academia have shown renewed interest in the region. Current publications have advanced the understanding of the tectonic evolution of the EKC, and its implications for mineral exploration (Orvik et al. 2025). However, other than several master theses, there has been little to no focus on the magmatic intrusions hosting the mineralization; the mineralization itself; and the local structural framework and controls on fluid flow. The current license holder, Kuniko Limited, carried out a range of exploration activities and defined a mineral resource estimate (MRE) for the Ni-Cu-Co Ertelien deposit (Kuniko Limited 2024). The remaining magmatic intrusions received less attention, with large but disparate datasets being produced over the years.

This PhD aims at utilizing the collected data, supported by field and laboratory work, to understand the structural regime across the region and increase the understanding of the controls on mineralization. This would allow the identification of high potential targets and the development of hypotheses which could be then tested by state-of-the-art exploration techniques, significantly enhancing the exploration efforts within the region.

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P24.2

Mineral trace element chemistries fingerprint Ni-Cu-PGE prospectivity

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The exploration and discovery rate of magmatic Ni-Cu-PGE sulfide deposits needs to increase to meet the global demand for renewable technologies. To aid in this endeavour, we have developed a method using trace element signatures in common minerals to assess the prospectivity of exploration regions.

We have examined the trace element content of spinel (chromite-magnetite), olivine, pyroxene, apatite and ilmenite to understand how these signatures vary between mineralised and unmineralised systems in both mafic-ultramafic intrusions and komatiites. We have created a large and robust mineral chemistry database from 1,160 rock samples collected from 12 case study areas in Western and South Australia. We have supplemented these with rock samples from world-class ore deposits globally.

The dataset contains over 11,000 individual mineral analyses and was interpreted using machine learning models to predict the likelihood of an individual mineral analysis being associated with magmatic sulfide mineralisation. Spinel analyses were the most numerous in this study, and this large dataset allows for confident predictions of whether the source was a mineralised or non-mineralised intrusion or flow. Further, trace element analysis of spinel shows the potential to indicate both prospectivity and sulfide volume which could vector toward more extensive and economic deposits. We show evidence that weathering and regolith formation have little effect on the trace element composition of spinel, making it an ideal resistant indicator mineral for exploration.

Other minerals, such as olivine, and pyroxene do not survive within regolith. However, these minerals still show potential for use as in-situ indicator minerals and for exploration in glaciated terrains. For example, pyroxene can be examined for trace element (Cr-Ti) variation within grains to understand if the sampled intrusion has the potential to be a magma conduit.

Our research shows that indicator minerals can be a valuable addition to the exploration toolkit, enhancing exploration globally.

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O25.1 (Keynote)

Paleomagnetism of Jurassic Vestfjella flood basalts of Antarctica

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The last supercontinent Pangea began fragmenting around 200 Ma to form the present-day continents. The initial stages of the break-up of southern part of Pangea, Gondwana, were marked by extensive mafic magmatism and lithospheric thinning around 180 Ma. Between the then-joined Grunehogna (modern East Antarctica) and Kalahari (southern Africa) cratons, this voluminous magmatism formed the Karoo and Ferrar continental flood basalts, part of the greater Gondwana Large Igneous Province. The Vestfjella mountains of Dronning Maud Land, East Antarctica preserve one of the most extensive Antarctic records of this event and provide a key for reconstructing the pre-breakup configuration of these cratons. Although geochemical and isotopic correlations between Antarctica and Africa are relatively well established, there is limited amount of paleomagnetic constraints from East Antarctica. High-quality data are therefore required to refine plate reconstructions and to better understand the magmatic and tectonic evolution of this part of Gondwana.

During two FINNARP expeditions in the late 90s, more than 400 oriented hand samples were collected from seven nunataks across the Vestfjella region. The dataset includes Jurassic flood basalts (~182-189 Ma) as well as younger intrusive rocks, such as ultrapotassic dykes with ages near 160 Ma. The volcanic suite is compositionally diverse, comprising both low- and transitional-Ti lava types. Several of these lava groups, as well as ferropicritic dykes, have close analogues on the Kalahari craton, highlighting strong intercontinental correlations.

We present new paleomagnetic and rock magnetic results from Jurassic volcanic and intrusive rocks in the Vestfjella region of Dronning Maud Land. Rock magnetic analyses suggest that pseudo-single domain magnetite is the dominant remanence carrier, yielding stable magnetizations. Thermal and alternating-field demagnetization experiments produce both normal and reverse directions. The reversals of the lavas are symmetric and yield a positive reversal test. The resulting polarity stratigraphy shows a shift from normal to reverse directions toward the base of the sequence, closely resembling magnetostratigraphy on the African side of the Karoo flood basalts. The ~182 Ma basalts provide paleomagnetic poles consistent with coeval Karoo data, supporting a close alignment of the Grunehogna and Kalahari cratons at the onset of Gondwana breakup.

O25.2 (PRESENTATION CANCELLED)

Precambrian supercontinents – current status with a special focus on Baltica

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We updated the Precambrian paleogeography of Earth during the last 3 b.y. using high-quality paleomagnetic and other data. Following the era of supercratons and independent drifts of the cratons/continents (3.0-1.9 Ga) two supercontinents can be envisaged: the Paleo-Mesoproterozoic Nuna (1.7-1.3 Ga) and the Neoproterozoic Rodinia (1.0-0.72 Ga). These supercontinents are different by their geometries but also by their kinematics and drift histories (Pesonen et al. 2021). Our continental reconstructions suggests that the Earth's surface consisted of four megacontinents (clans of continents). The Laurentian clan (Laurentia, Siberia, Baltica) remained nearly intact and, after broken-up from the Nuna supercontinent (1.3 Ga), drifted and rotated with high velocities to polar latitudes and back to equatorial latitudes, finally docking with other megacontinents to form Rodinia (1.0 Ga). The Australian (N-, S-, W-Australia and India) and the Chinese (N- and S-Chinas, Tarim) megacontinents followed the Laurentian clan with some reorganizations. The Amazonian clan (Amazonia, Congo-São Francisco, West Africa, Rio Plata and Kalahari) remained in southern hemisphere near Equator experiencing huge rotations before docking with other megacontinents into the Rodinia supercontinent (at 1.0 Ga). The latitudinal lock in curves reveal dispersions (marking independent drifts), followed by lock in (birth of supercontinent) and by new dispersions, as also seen in dynamic models of the lithosphere of Earth. The plate velocity curves of the continents reveal considerable variations with three "lulls" (slow downs). Although the very high pole velocities, observed in Stenian data of N. China, may hint to a rapid TPW event, we note that the overall shape of the global velocity curve compares with those of zircon age, metamorphic probability, subduction activity, $d^{18}O$ and frequency of LIPs, suggesting that interactions between the crust and mantle takes place. A noticeable feature in the global plate velocity curve is the distinct minimum during the Nuna tenure (1.6-1.4 Ga) when A-type granite activity is at maximum. These data, collectively, suggest that plate tectonics, rather than stagnant lid tectonics, operated during the last 3 billion years including the "boring billion (1.8-0.8 Ga) and the plate velocity shut downs. We also present an animated drift history of Baltica and show that the geological neighbors of Baltica in the core of Nuna supercontinent were Laurentia (Greenland), Siberia, Amazonia, Congo-São Francisco and West Africa.

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025.3

Preliminary paleomagnetic data on Archean–Paleoproterozoic mafic dykes in the Kola craton

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Mafic dyke swarms are fundamental to constraining the timing and mechanisms of cratonic drift. They provide robust geochronological information and frequently preserve stable remanent magnetization, recording ancient geomagnetic field directions that yield critical constraints on paleolatitude. Paleomagnetic studies are thus central to reconstructing the configuration and evolution of early cratonic realms during the Paleoproterozoic. Competing paleogeographic models propose either a single supercontinent or multiple drifting supercratons, such as Superia, which included the Kola, Karelia, and Superior cratons (Salminen et al. 2021), making high-quality paleomagnetic data from Kola mafic dykes essential. Available Fennoscandian data are limited: Karelia has a single 2.68 Ga pole, seven 2.5–2.45 Ga poles shared with Kola, and eleven 2.05–1.75 Ga poles (e.g., Evans et al. 2021), while 1.76 Ga Kola poles are lacking and the 2.68 Ga Kola pole (Veselovskiy et al. 2024) derives from a single dyke and does not average secular variation.

Samples were collected from mafic dykes in the Archean basement of Finnmark, northern Kola craton, representing three generations: deformed ~2.7 Ga dykes (U-Pb zircon age, Vogt, 2024), undeformed dykes cutting the 2.7 Ga dykes (assumed 2.4–2.2 Ga, Vogt 2024), and 1.76 Ga dykes (Vogt 2024). Thermal and alternating field demagnetization, supported by rock magnetic analyses, indicate magnetite as the primary magnetic carrier. The three 1.76 Ga dykes exhibit northerly declinations and intermediate downward inclinations, consistent with coeval Karelia data (e.g., Evans et al. 2021). Among the undeformed dykes, five show northerly declinations with steep downward inclinations, and one shows a southerly declination with steep upward inclination, yielding a positive reversal test. While the Kola craton lacks data for 2.44–2.06 Ga comparison, these directions are consistent with the directions obtained from the single 2.68 Ga Kola dyke (Veselovskiy et al. 2024). Deformed ~2.7 Ga dykes record magnetization intermediate between the younger dykes, suggesting remagnetization during the younger events.

We suggest that the 1.76 Ga and undeformed dykes reliably record the Earth's magnetic field, constraining the Kola craton's paleogeography, while deformed ~2.7 Ga dykes were likely remagnetized. These results fill critical gaps in Kola's record and provide new constraints for reconstructing the Superia supercraton.

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O25.4

Supercontinent Cycles and the Stability of Earth's Magnetic Field

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Earth's magnetic field, which is produced by convection in the liquid outer core, occasionally undergoes polarity reversal. The frequency of these reversals has fluctuated over the course of geological history. While certain intervals were characterized by frequent shifts, others experienced long-lasting stability (superchrons). There is increasing evidence that large-scale tectonic processes have an impact on reversal behavior (Pétreilis et al. 2011). It is unclear whether comparable modulation was in effect during the Proterozoic supercontinent cycles. Here, we present a first-order analysis of reversal behavior across two Proterozoic supercontinents: Nuna/Columbia [assembly-coherent state ~1800–1380 Ma; breakup ~1380–1100 Ma (Salminen et al. 2024)] and Rodinia [assembly-coherent ~940–880 (820) Ma; breakup ~820–600 Ma (Evans 2021)]. We compiled a global paleomagnetic dataset spanning 2200–600 Ma, screened for geochronological precision ($\leq \pm 20$ Myr), quality scores of $Q \geq 4$ or $R \geq 4$, and clear polarity classification (Driscoll & Evans 2016). From the site-mean data we calculated polarity ratios, which quantify the proportion of normal to reversed directions and serve as a proxy for reversal probability.

Our results suggest systematic modulation of reversal frequency across supercontinent cycles, with polarity ratios differing consistently between assembly and breakup intervals. The precise direction of change depends on how supercontinent boundaries are defined, but robustness tests indicate that a significant signal persists despite dating uncertainties. Comparison with Proterozoic paleointensity data shows that intervals of high polarity ratio coincided with stronger field intensity, particularly between 1200 and 1000 Ma. Although the number of high-quality Proterozoic poles remains limited, the dataset is steadily expanding and will enable more stringent constraints soon.

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O25.5

Oroclinal Orogens: Paleogeographic and tectonic implications

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Bent orogens, referred to as oroclines, are enigmatic tectonic features. The scale of oroclines can be enormous. Much of the Alaskan and Iberian peninsulas are attributable to coupled oroclines of the Cordilleran and Variscan orogens, respectively. Paleomagnetic, structural and stratigraphic data demonstrate that these orogens were linear features that were subsequently folded about vertical fold axes. Attempts at analogue modelling of oroclines as buckled lithospheric beams have failed, calling into question plate-scale palinspastic restorations of oroclines, and interpretations and models of oroclinal orogens as products of buckling of lithospheric-scale beams. In essence, neither the crust nor the lithospheric mantle have the strength necessary to buckle at the required scale.

An alternative interpretation is that oroclines are akin to wind-blown pond scum that deforms against a buttress. In the case of oroclines, deformation is driven by a mantle wind; the pond scum represents a thin, upper crustal layer that detaches from the underlying crust and mantle; and the buttress is likely provided by a convergent continental margin. An appropriately oriented mantle wind appears to have been present during the formation of the Cordilleran and Variscan oroclines. In the Cordillera, a consistent north-blowing mantle wind explains the northward translation of terranes and continental ribbons since the Jurassic, a process that is ongoing as indicated by Global Navigation Satellite System (GNSS) velocity vectors and the broad array of active dextral strike-slip structures. Similarly, a north-blowing mantle wind explains the consistent south-to-north transfer of Gondwana-derived terranes that were swept across the intervening Iapetus-Rheic-Tethyan oceanic realm before accreting to the Laurentian-Baltic-Asian upper plate in advance of the terminal Pangea-forming collisional event. In both cases, detachment and vertical axis folding of a thin, crustal lid accompanied interaction with a continental buttress (the Siberian craton in the Cordilleran case, and Laurentia-Baltic in the Variscan). The pond scum model implies that oroclines are allochthonous with respect to the crust and lithospheric mantle that currently underpins them; and that oroclines detach from the underlying plate during deformation.

O25.6

From Nuna to Rodinia: Geodynamic implications of the paleomagnetic record of Congo–São Francisco craton

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Reconstructing ancient paleogeography is fundamental to understanding Earth's tectonic evolution. Three supercontinent cycles are recognized—Nuna/Columbia, Rodinia, and Pangea—each potentially preceded by an intermediate landmass such as Umkondia before Rodinia and Gondwana before Pangea. The Congo–São Francisco (C/SF) craton, a central element of Gondwana, has been proposed as part of Umkondia, but its role in earlier supercontinents remains debated.

To address this, large igneous province (LIP) records (1500 Ma, 1385 Ma, 1100 Ma) were combined with paleomagnetic data from the C/SF craton to evaluate its history across the Nuna–Rodinia transition. The robust 1500 Ma pole from SF positions C/SF near Amazonia–West Africa and the Nuna core (Laurentia–Baltica–Siberia), supporting its participation in Nuna. However, the 1385 Ma pole from Congo implies $\sim 85^\circ$ azimuthal rotation and major transform motion between 1500 and 1385 Ma, consistent with early Nuna breakup and setting the stage for Rodinia assembly (Salminen et al. 2024). A further large rotation relative to Laurentia is required between 1385 Ma and the Neoproterozoic, underscoring C/SF's complex role in Rodinia.

Within this framework, widespread ~ 1100 Ma magmatism in Congo, Kalahari, India, and Amazonia (Ernst et al. 2013; Choudhary et al. 2019) has been used to propose Umkondia, envisioned as a “megacontinental” (Wang et al. 2020) bridge between Nuna and Rodinia. Paleomagnetic data at 1110 Ma support a direct Congo–Kalahari connection, consistent with earlier LIP correlations (Ernst et al. 2013; Salminen et al. 2018). Yet divergent coeval poles indicate persistence of a substantial ocean after 1110 Ma, suggesting Umkondia was not a stable long-lived entity (Salminen et al. 2018). Instead, Congo and Kalahari likely approached one another only during Rodinia assembly and remained central in Gondwana.

These results show that the C/SF craton participated in Nuna, underwent large-scale rotation and transform motion during its breakup, and later contributed to Rodinia. This highlights that supercontinent transitions were not linear but dynamic, involving major cratonic reorganizations and diachronous assembly. The evidence challenges the stability of Umkondia as a long-lived continental entity, instead suggesting a transient cluster formed during plume-driven magmatism. Collectively, these findings imply that supercontinent evolution was governed by episodic mantle–lithosphere interactions, with transient continental groupings and large craton rotations playing key roles in modulating the supercontinent cycle.

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O25.7

Scouring the seas for signs of true polar wander

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True polar wander (TPW)—the reorientation of the solid Earth relative to the planetary spin axis—is presently occurring at a rate of about 10 cm/yr, exceeding the mean rate of differential plate motion. Of debate is whether this rate is transient and negligible on geological timescales, or whether Earth has experienced episodes of rapid TPW lasting millions of years. Paleomagnetic evidence has increasingly been cited to support proposals of especially fast TPW in the Mesozoic, Paleozoic, and Precambrian, but the absence of an absolute plate-motion reference frame and limitations of the paleomagnetic record have impeded definitive testing. Rapid TPW will induce global sea-level fluctuations associated with relative changes in centrifugal potential, offering an independent test. Here we evaluate this prediction using continental flooding reconstructions and discuss the evidence for rapid, large-amplitude TPW in the Phanerozoic.

O25.8

Ediacara obscura: Unveiling hidden magnetisations in the Fen carbonatite complex

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Paleomagnetic directions from Ediacaran (635 – 539 Ma) rocks are widely dispersed, which has led to conflicting hypotheses about tectonic regimes and geomagnetic field behaviour during that time, and raised doubts about the fidelity of the paleomagnetic record. In particular, data from eastern and western Baltica show large and rapid changes in paleopole positions which are difficult to explain if we assume the Ediacaran field followed the geocentric axial dipole hypothesis.

We present new paleomagnetic data from 214 samples across 18 sites of the Fen carbonatite complex (ca. 585 Ma) in southern Norway, coupled with scanning electron and quantum diamond microscopy, alongside detailed rock magnetic and geochemical analyses. Our results indicate that the Fen complex and its associated intrusions were pervasively overprinted in the Permo-Carboniferous (ca. 300-275 Ma), during tectono-magmatic activity of the nearby Oslo Rift, which complicated previous paleomagnetic interpretations. However, after removing secondary overprints, we find that ca. 7% of our samples preserve weak, shallow paleodirections which are interpreted as primary. The outlier directions are found in rock types not previously studied, mainly damtjernites (i.e. ultramafic lamprophyre intrusions).

Based on these directions, we define a new paleopole at 267.9° E, 2.8° S ($dp/dm = 2.7^\circ/5.3^\circ$, $n = 15$) which supports a low-latitude/equatorial position for Baltica during the mid-Ediacaran. Our findings have significant implications for understanding Baltica's paleogeography in the late Neoproterozoic and the extraordinary climatic and fossil record of the time.

O25.9

Investigating anomalous behaviour of Earth's magnetic field in the mid-Palaeozoic – preliminary palaeomagnetic results from Silurian Ringerike sandstone of the Oslo Region, Norway

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The late Silurian to the early Carboniferous (~440-340 million years ago) represents a palaeomagnetic data gap with a scarcity of high-quality palaeomagnetic results. It has proven particularly difficult to establish characteristics of the Devonian magnetic field, and one hypothesis is that the seemingly ubiquitously weak Devonian magnetisations may be a result of a weak dipole at this time.

It is commonly agreed that the Earth's magnetic field experienced periods of stability and few polarity reversals in the Ordovician and late Carboniferous-Permian periods, but it is not clear if the shifts between these strong and stable magnetic fields and the weak and/or unstable magnetic field of the Devonian were gradual or rapid. The periods leading up to and immediately following the proposed dipole low may be studied to constrain the start and end of the time of instability, as well as to learn more about how the magnetic field behaves in such transitional periods.

Frequent polarity reversals may be linked to weak dipole moment and low field strength, and determining the reversal rate of the Earth's magnetic field in the middle to late Silurian is therefore of particular interest. A comprehensive magnetostratigraphy for the Silurian is currently not available, but previous work from the redbed Ringerike sandstone from the Oslo Region, Norway has shown promising results. I will present preliminary results from palaeomagnetic analyses performed on samples of the middle to late Silurian Ringerike sandstone and discuss the broader implications of these results for our understanding of the geomagnetic field at this critical time.

O25.10

Testing the Mesozoic dipole low hypothesis in Amazonia

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Reliable reconstruction of the geomagnetic field requires robust paleomagnetic records, yet obtaining paleointensity data remains a challenging task across the geological timescale. The Jurassic dataset is uneven in both quality and geographic distribution, and such dataset tend to support a picture of lower than modern geomagnetic dipole moment / weaker field strength across much of this interval (especially from ~200 Ma onward). This is the Mesozoic dipole low hypothesis (Prévot et al. 1990). Earliest times (210-200 Ma) have much sparser data, and it is less clear how strong or weak the field was then, and whether the decline into the Mesozoic Dipole Low had already begun or not. This preliminary study attempts to get new robust paleointensity data at ~200 Ma for the French Guianan dykes of the Central Atlantic Magmatic Province (CAMP). These mafic dykes were already studied to get a robust paleomagnetic pole and such rocks showed a stable remanence promising for this paleointensity study (Nomade et al. 2000). These preliminary results will help to constrain the debated onset of the Mesozoic Dipole Low and test whether the observed low values are a global or regional feature.

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O25.11

High-resolution Holocene paleosecular variation from coastal Baltic sediments, western Finland

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Oxygenation dynamics in coastal sediments provide critical insights into Holocene environmental change, yet the timing of these events in northern Europe remains poorly constrained. In this study, we analyse a 30-meter marine–lacustrine sediment sequence from Kurikka, western Finland, to reconstruct the pace and duration of oxygen fluctuations during the Holocene Thermal Maximum and subsequent Littorina phase. Previous findings suggest that deoxygenation in the Bothnian Sea was common but frequently interrupted, though the precise chronology of these events has remained unresolved (Silvennoinen et al. 2025).

To establish a robust temporal framework, we produced a high-resolution paleosecular variation (PSV) record of inclination and relative declination. Paleomagnetic and rock magnetic analyses show both magnetite (Fe₃O₄) and greigite (Fe₃S₄) carry a stable remanence. Measurements at 5 cm resolution yield a decadal-scale PSV curve covering ~5000 years, and the record can be correlated to the regional stacking curve (FENNOSTACK (Snowball et al. 2007)) and to the closest regional curves (Haltia-Hovi et al. 2010; Lougheed et al. 2012; Ojala & Saarinen 2002). Coupled to an age-depth model based on ten radiocarbon dates from macrofossils and bulk sediment, this record will provide precise age control for major environmental transitions, including the lacustrine–marine shift and intervals of hypoxia. Furthermore, we explore the possibility for relative paleointensity reconstruction using the pseudo-Thellier method (Tauxe et al. 1995).

The continuous, high-accumulation record from Kurikka captures short-term Holocene geomagnetic field variations that may be smoothed or lost in lower-resolution archives. The record has the potential to serve as a high-resolution new master curve for northern Baltic Sea region and will support future modelling efforts of magnetic field evolution.

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P25.1

Whole rock versus single crystal multispecimen paleointensity: insights from Early Mesozoic dykes and Permian gabbros

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Reliable estimates of geomagnetic field strength are fundamental to understanding the long-term behavior of the geodynamo, yet paleointensity determinations remain uneven and challenging across the geological record. This study compares whole-rock and single-crystal paleointensity approaches on two well-characterized intrusive collections: ~200 Ma mafic dykes from French Guiana and ~275 Ma anorthosites/gabbros from the Oslo Rift in Norway. We used a multispecimen approach both for whole rock (*i.e.*, cylindrical specimen of 11cm³) and single crystal (~2-3 mm plagioclase) paleointensity by using an unique FURemAG prototype furnace developed at Géosciences Montpellier (Poidras et al. 2012). The paleointensity results of the most promising sites will be discussed with the obtained magnetic mineralogy by using conventional hysteresis, isothermal remanence curve, FORCs, and magnetic imaging. Our results aim to clarify the strengths and limitations of multispecimen methods for single crystals, refine the contribution of intrusive complexes to the global paleointensity database, and provide new constraints on geomagnetic field intensity across the Permian–Jurassic interval.

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P25.2

LithoPlates: Integrating Samples, Metadata, and Reconstructions for Deep-Time Paleogeographic Analysis

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LithoPlates is a digital platform designed to connect geoscientific sample data and metadata with published paleogeographic reconstructions. By integrating laboratory outputs and geochemical and geochronological information into evolving plate models, LithoPlates enables researchers to interrogate where and when samples fit within the context of Earth's evolution.

The platform created with the help of the EarthByte group (GPLates) provides a FAIR, structured environment where data can be visualized, filtered, and queried across geological time. Instead of requiring users to develop complex scripts or custom pipelines to build interactive reconstructions, LithoPlates offers a streamlined but powerful alternative. Samples and their metadata can be explored directly within reconstructed plate configurations, enabling spatial and temporal comparisons between datasets and models with minimal technical barriers.

LithoPlates builds on eight published models, embedding these models within an interactive framework that links them directly to curated sample data. Through direct API connections and flexible export formats, LithoPlates supports interoperability with external analytical frameworks, statistical tools, and machine learning approaches. Researchers can cross-compare existing reconstructions, test hypotheses about terrane movements, or track the geological history of regions of interest using curated sample datasets anchored in robust metadata.

We demonstrate case studies where LithoPlates has been applied to integrate geochronological and thermochronological data within regional models. These examples illustrate how the platform bridges raw data and reconstructions, providing a transparent, digital framework that strengthens reproducibility and expands the scope of paleogeographic research. By aligning community datasets with plate models, LithoPlates creates new opportunities for collaborative, data-driven exploration of Earth's deep-time history.

027.1

Twenty-five million years of monazite growth in a migmatitic pelitic schist of the upper structural level of the Great Himalayan Sequence, Macchermo Valley, Nepal

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A Biotite-Sillimanite-Garnet (Bt-Sil-Grt) migmatitic pelitic schist specimen was collected in the Macchermo Valley of the Khumbu region of Nepal in order to reconstruct a Pressure-Temperature-time (P-T-t) path for the upper part of the Great Himalayan Sequence. The foliation in the specimen is defined by Sil-Bt seams, originating from highly resorbed and elongate Gt. In outcrop, the pelitic schist is crosscut at shallow angle by a leucogranite dyke. Quantitative chemical maps were constructed with the software XMapTools using data from a scanning electron microprobe. Phase equilibria forward modeling (PEFM) was conducted with Perple_X. For the suprasolidus path, PEFM was conducted from the chemical composition derived from an area interpreted as in textural equilibrium. The modes of Sil-Bt-Gt-Plagioclase (Pl) and the compositional isopleths for pyrope and grossular in Gt core, anorthite in Pl core and TiO₂ in Bt all intersect in a narrow PT field centered at 740 °C and 450 MPa, consistent with PT conditions estimated with conventional thermobarometry. Ca zoning in Pl and Gt, as well as Mg zoning in Gt and Bt indicate Gt breakdown; conventional thermobarometry calculated from Gt-Pl-Bt in contact with each other yielded conditions of ~ 650 °C and 200 MPa. For the subsolidus part, PEFM was conducted by reintegrating melt in a stepwise fashion for a total of 11 vol% melt. Monazite U-Th-Pb geochronology was conducted *in situ* within the studied thin-section by laser ablation ICP-MS. Early monazite growth between ca. 45 and 30 Ma is characterized by a trend of increasing Y, but stable Eu anomaly, toward younger dates. Monazite growth was less abundant between ca. 30 and 19 Ma and is characterized by a trend of both increasing Y (steeper than earlier dates) and Eu anomaly with younger dates. These trends are interpreted to reflect progressive Gt breakdown during the older monazite growth phase (45-30 Ma) followed by a more pronounced Gt breakdown accompanied by feldspar crystallization during the younger (30-19 Ma) phase.

The new data reported herein outline a P-T-t path with protracted monazite growth between ca. 45 and 30 Ma during nearly isobaric heating at P of 600 - 800 MPa. Once the schist reached partial melting conditions, it started a nearly isothermal decompression path at T of 675-750°C between ca. 30 and 19 Ma until it crossed the granitic solidus at a P of ~200 MPa. This P-T-t path is very similar to that obtained in the channel flow, thermomechanical model HIIT of Jamieson et al. (2006) for a particle (G3) at a similar structural level than the studied specimen. This is one of the few Himalayan sample to record almost entirely the HT orogenic event of the Great Himalayan Sequence from 45 to 19 Ma.

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O27.2

Nanorock crystallization and entrapment dynamics in zircon of a polymetamorphic garnet-free granulite

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Partial melting, along with the evolution and migration of melts, plays a crucial role in shaping the continental crust. These processes influence the transport and concentration of metals, the cycling of volatile components, and the crust's mechanical behaviour. Over recent decades, the study of nanorocks—crystallized melt inclusions (Bartoli & Cesare 2020)—has become a vital method for understanding melt evolution, as these inclusions are believed to preserve original melt characteristics (Cesare et al. 2015). While much research has focused on nanorocks within garnet, there is growing interest in melt inclusions found in zircon because (i) the major elements forming nanorocks, except for SiO₂, are absent in the host mineral, and (ii) zircon forms through various (re)crystallization processes, potentially recording different stages of metamorphic evolution.

Garnet-free granulites from the Guaxupé nappe (Brazil) record a complex history from protolith crystallization at ca. 2.55 Ga to ultra-high temperature (UHT) metamorphism at ca. 650–590 Ma. The zircon crystals contain crystallized melt inclusions ranging in size from 1 µm to 15 µm distributed in cores and rims. MicroRaman spectroscopy combined with field emission gun electron probe microanalysis revealed that these inclusions consist of variable combinations of mostly cristobalite/quartz, kochetavite, kumdykolite, "phase 430", carbonate and, biotite and/or white mica. The re-homogenized nanorocks have a metaluminous to peraluminous composition, varying from granodioritic to granitic. These results were compared with the composition of stromatic granulite obtained from quantitative micromaps and bulk rock of outcropping segregated leucosomes. The lower concentration of CaO, MgO, P₂O₅ and TiO₂ and the TE signature suggest that the nanorocks represent melts formed at lower temperatures than those formed during UHT conditions recorded in the leucosomes. Thus, the nanorocks may have been trapped in zircon during prograde metamorphism. This hypothesis is consistent with the CL images and the U-Pb (LA-ICP-MS) data, which show that the nanorocks are hosted in zircon domains recording discordant dates in line with partial resetting of Archean ages, rather than being formed during UHT metamorphism in the Neoproterozoic. The homogeneous composition of the inclusions and their location in cores and rims, disfavour the interpretation that the nanorocks record igneous crystallization. We propose a mechanism of melt inclusion entrapment that involves metamictization that creates porosity, melt infiltration and annealing, resulting in the formation of melt inclusions that are secondary in nature but primary in appearance and record prograde to peak melts.

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027.3

Mountains from sand grains: Advances in detrital provenance applied to orogens

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Detrital geochronology is a powerful tool to interrogate the sedimentary archive of (paleo-)hinterland tectonism, metamorphism, and exhumation, and can also be applied to modern river sediment as a first-pass tool to establish regional bedrock ages. The popular zircon U-Pb detrital geochronometer has seen widespread adoption for these tasks (4,708/5,670 results for the search term *detrital geochronology* also contain the term *zircon U-Pb*; *Clarivate Analytics Web of Science*). However, zircon fertility is strongly biased to intermediate to felsic source rocks. Moreover, zircon crystallization is volumetrically limited in metamorphic terranes which do not achieve anatexis (e.g., Moecher & Samson 2006), and is typically restricted to rim overgrowths which are vulnerable to mechanical destruction during fluvial transport, and which are challenging to detect and analyse (e.g., Campbell et al. 2005; Liu et al. 2025).

Therefore, it is desirable to develop complementary provenance tools for sub-anatectic settings, as well as tools targeting more abundant rock-forming minerals for use with small-volume samples (e.g., drillcore). Established alternative detrital phases include the U-Pb system in apatite, monazite, titanite, and garnet. The advent of LA-ICPMS systems equipped with mass-filtered online reaction cells now also permits the routine use of β -decay systems by overcoming parent-daughter isobaric interferences. These include Lu-Hf in garnet and apatite, and Rb-Sr in K-phases including K-feldspar and mica (Rösel & Zack 2022; Woods 2016). K-phases are also amenable to conventional Ar-Ar detrital geochronology.

Here, we present case studies of emerging detrital provenance techniques, with particular application to modern and past orogenic systems.

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O27.4

A chevkinite, astrophyllite and aenigmatite-bearing monzonite, tales from a 1330 Ma metamorphic alkaline rift at Balltorp, SW Sweden

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Alkaline rocks have long been a prime target for REE-exploration. Linking *in situ* geochronology to detailed petrography and mineralogy greatly improves our understanding of the cryptic effects that metamorphism exhibit on alkaline rocks, and thus HFSE and REE mobility.

The Balltorp monzonite was first recognized by Lundegård (1953) as a “red-grey to red, predominantly acidic, alkali-rich gneiss”. On the basis of this and the U and Th radiation maps the rock was targeted for Be-exploration in the 1980’s but only slightly elevated Be-concentrations were found, however the whole rock data indicate a strong enrichment of Zr, Ti and LREEs (Holmqvist 1989). New detailed mineralogical studies show that rocks are dominated by albite, microcline, arfvedsonite, aegirine, zircon and fluorite, additional minerals include monazite-(Ce), chevkinite-(Ce) ($\text{Ce}_4(\text{Ti}, \text{Fe}^{2+}, \text{Fe}^{3+})_5\text{O}_8(\text{Si}_2\text{O}_7)_2$), ilmenite, astrophyllite ($\text{K}_2\text{NaFe}^{2+}_7\text{Ti}_2\text{Si}_8\text{O}_{26}(\text{OH})_4\text{F}$), aenigmatite ($\text{Na}_4[\text{Fe}^{2+}_{10}\text{Ti}_2]\text{O}_4[\text{Si}_{12}\text{O}_{36}]$), chamosite and bastnäsit-(Ce).

A few preserved zircon cores yield a magmatic U-Pb age of 1322 ± 10 Ma, these zones are internally homogenous but display an embayed and corroded contact towards other parts of the zircon. The retrieved age is coeval with rocks of the Kungsbacka bimodal suite (Hegardt et al. 2007), which consists of both granitic and gabbroic intrusive magmas. However, the majority of zircon grains yield a Sveconorwegian metamorphic age at 1035 ± 8 Ma. U-Pb dating of monazite-(Ce) from the same rock yield similar metamorphic ages.

Chevkinite-(Ce) usually occur as large grains, commonly metamict and have broad rims of glass (enriched in LREE, Ti and F). Normally astrophyllite occurs as a primary phase in silica-undersaturated rocks, however at Balltorp, textural evidence suggests that the astrophyllite formed during the waning stage of the Sveconorwegian. The breakdown of silicates and fluorite, and by metamictization of chevkinite-(Ce), which liberated the necessary chemical constituents to the fluid could have facilitated the late astrophyllite crystallization.

In situ single spot Rb-Sr dating in microcline yields an age of 898 ± 6 Ma indicating conditions of slow cooling (or possible reheating) during the Sveconorwegian orogeny. These new observations confirm the presence of alkaline intrusive rocks associated to the anorogenic magmatism at around 1330 Ma in the Idefjorden terrane.

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O27.5

In situ Lu-Hf petrochronology of plutonic carbonatites from Finland

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In situ determination of Lu-Hf isotope ratios enables dating of several mineral phases, including calcite and apatite (Glorie et al. 2023; Simpson et al. 2022) which are typical mineral phases in plutonic carbonatites. The key aim of this work is to determine whether the Lu-Hf system can be used to constrain the age of carbonatite emplacement or to discern separate magmatic stages. We analyzed apatite and calcite for Lu-Hf isotope dates from three different plutonic carbonatites in Finland, ranging in age from the Neoproterozoic to Upper Devonian.

Thirteen samples from Siilinjärvi glimmerite-carbonatite complex, Halpanen carbonatite dike, and Sokli carbonatite complex were studied for Lu-Hf isotopes at Adelaide Microscopy (University of Adelaide, Australia) using *in situ* laser ablation inductively coupled plasma tandem mass spectrometry, followed by monazite U-Pb analysis of one Siilinjärvi sample by LA-single collector-ICP MS at the Geological Survey of Finland.

Apatite and calcite (and a single dolomite) from Sokli and Halpanen yield Lu-Hf dates (360–380 Ma and 1794 Ma, respectively) similar to published reference ages, within uncertainty. Siilinjärvi results however have Lu-Hf dates incongruent with the ca. 2.6 Ga zircon U-Pb age (Rukhlov & Bell 2010). The apatite and calcite Lu-Hf dates are decoupled (1.97–2.2 Ga and 1.8–1.86 Ga, respectively). The results indicate closure of the Lu-Hf system in the Paleoproterozoic for calcite grains, likely due to complete resetting of the system during the Svecofennian orogeny. The apatite Lu-Hf system has been disturbed after Neoproterozoic crystallization but closed prior to the orogeny at ca. 2 Ga (complete re-equilibration) or a result of a mixed signal between primary and disturbed isotope compositions (partial re-equilibration), yielding older isochron dates. Monazite U-Pb from the Siilinjärvi sample yields a Tera-Wasserburg lower intercept date of ca. 1.77 Ga. Based on the result, the monazite in the sample was formed in a metasomatic reaction between apatite and a fluid in the late stages of the Svecofennian orogeny.

The *in situ* Lu-Hf system can provide meaningful age information from apatite and calcite from carbonatitic samples, providing emplacement ages (Halpanen and Sokli) or timing of post-magmatic processes (Siilinjärvi).

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O27.6 (Keynote)

Garnet chronology – a holistic perspective

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Garnet unifies the Big Four of relevant parameters in metamorphic petrology (pressure, temperature, deformation and time) in its composition and texture, and enables constraints on fluid flow through its trace-element and stable-isotope (e.g., O, Li, Fe) composition and zoning. These aspects make garnet

an unparalleled repository of geological information. Placing this record in time through direct garnet dating has been possible since 1980, when garnet in Norwegian eclogites was first successfully dated using the Sm-Nd system. Since then, the technique has taken flight with the development and calibration of Lu-Hf garnet dating, and more recently in-situ Lu-Hf and U-Pb garnet dating. While “ex-situ” bulk-garnet Lu-Hf dating enables extreme precision, the in-situ techniques pave the way forward to allow rapid age determination at sub-millimeter spatial resolution.

Anno 2026, the field of garnet chronology is at an exciting point, where multiple complementary techniques are available and can be integrated with elemental mapping to unpack the history of metamorphic rocks from the crust and mantle. While in-situ techniques are improving on precision and reference materials, so do ex-situ techniques on sample-size requirements and spatial resolution. This situation raises a series of interesting questions: How do the dating approaches compare? How low can we go in spatial resolution vs. uncertainty? Which approach works best or is perhaps “good enough” in a given case? Which system has the best memory and why? Is there anything we can’t do? And what about using REE signatures in accessory minerals to indirectly date garnet? So widely used the past decade and still common, but – when contrasted with direct garnet dating – how does it hold up?

This presentation will focus on the current status of the field, investigate the meaning of garnet Lu-Hf ages, and explore frontier applications of high-precision Lu-Hf garnet chronology in the study of metamorphic processes in the mountain belts, subduction zones and the cratonic mantle.

O27.7

Unraveling the metamorphic history and ore mineral remobilization of the Pyhäsalmi VMS halo: new insights from *in situ* Lu-Hf garnet geochronology, P-T-t modeling and Micro-CT

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Our study area, the Pyhäsalmi region (1.92 Ga), hosts Paleoproterozoic VMS deposits, located between the Archean basement and Paleoproterozoic Svecofennian crust in the Fennoscandian Shield. This economically important region has predominantly experienced four phases (D1-D4) of compressional deformation history between 1.91 and 1.79 Ga (Laine et al. 2015). This study unravels the tectono-metamorphic evolution of the Pyhäsalmi halo supracrustal rocks using *in situ* Lu–Hf garnet geochronology and constrains their P–T–t path from equilibrium mineral assemblage modelling. Additionally, we study microstructures in 2D and 3D to tie regional polyphase deformations with porphyroblast growth and sulfide remobilization.

In situ Lu-Hf inverse isochron ages from Pyhäsalmi garnets indicate two distinct metamorphic events: (i) cluster-type Fe-Mn-rich homogeneous garnet with ages of 1895 ± 53 Ma, likely representing the earliest metamorphic events during the D1-D2 compressional phase (collision); and (ii) corona-type with ages of 1824 ± 16 Ma and elongated garnets with ages of 1802 ± 7 Ma, with Mn-rich core denoting the second metamorphic event during the D4 compressional phase (predominantly post-collisional shearing). The preliminary P-T path for the supracrustal rocks indicates medium- to high-grade amphibolite facies metamorphic conditions with two prograde evolutions, with first peak conditions of 4–5 kbar at 550–600°C, indicated by cluster-type garnet + cordierite + plagioclase + biotite, and with second peak conditions (M2) of 5–6 kbar at 700–720°C, represented by corona and elongated-type garnet + sillimanite + cordierite + biotite. Petrographic and mineralogical evidence highlights late-stage retrograde hydrothermal activity, marked by intense chloritization of sillimanite, garnet, biotite, anthophyllite, and cordierite, and epidotization of plagioclase. Moreover, micro-CT analysis illustrates two distinct periods of sulfide remobilization from the halo region: (1) mechanical remobilization (solid-state) processes during the D1-D2 phase at 1.91 Ga associated with cataclastic flow, dislocation flow, and translation-gliding of pyrite and pyrrhotite, and (2) mixed-state remobilization (solid-liquid) processes linked with the D4 phase at 1.82–1.79 Ga denoted by sulfide redistribution into fractures and the hinge zone of crenulation cleavages (Islam et al. 2025).

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O27.8

Capturing crustal foundering in the act through integrated zircon, monazite, rutile and garnet petrochronology on high-pressure xenoliths

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Crustal foundering is one of the most important processes in the differentiation and recycling of the continental crust. Nevertheless, little is known about the timescale of foundering and its role in orogen dynamics. Lower crustal xenoliths from the Pamir Mountains, Tajikistan, provide a unique opportunity to study this process. The rocks comprise well-preserved eclogite and high-pressure felsic granulite (peak conditions: 2.5-2.8 GPa and 1000-1100 °C), which were erupted c. 11 Ma (Hacker et al. 2005). Xenolith samples were subjected to coupled in-situ U-(Th-)Pb geochronology and trace-element analysis of zircon, monazite and rutile by laser-ablation (split-stream) ICP-MS, and garnet Lu-Hf chronology. Rutile U-Pb ages match the age of eruption (11.17 ± 0.06 Ma), showing that rutile in xenoliths can be used to reliably and precisely date magmatic processes (Zack & Kooijman 2017). Zircon and monazite yielded distinct age clusters between 60-11 Ma (Kooijman et al. 2017). Specific populations occur among different samples, but are never represented in both zircon and monazite in single samples, showing that these petrochronometers are complementary and are best both applied to resolve metamorphic histories. Monazite inclusions in garnet suggest initial burial and prograde garnet growth at c. 40 Ma. Garnet Lu-Hf dating confirms this texture-based inference, yielding precise isochron ages between 41-38 Ma (Tual et al. 2022). Together, the data from zircon, monazite and garnet show that the rocks were buried to c. 40 km depth along a stable continental geotherm from 40 to 20 Ma, when they melted and became deeply buried. The rocks traversed the Moho (70 km) by 13 Ma and reached c. 90 km by 11 Ma, by which time burial rates were an order of magnitude higher than at the onset of burial. This detailed record is the first to capture crustal foundering in the act. This process introduced vestiges of old evolved crust into the mantle on a 10-Myr time scale, which is far shorter than the magmatic history associated with mountain building in the region. This recycling process thus can explain the variability in the radiogenic isotope signatures of Cenozoic mantle-derived magmatic rocks in the Pamir Mountains and neighbouring Tibetan Plateau without requiring a change in plate dynamics or source region.

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O27.9

Constraining the prograde metamorphic evolution of the southern Western Gneiss Region recorded in garnet zoning

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Garnet has long been regarded as the most important metamorphic mineral as it can preserve a temporal and thermobaric record of a metamorphism. Pressure–temperature (P – T) information is recorded in the chemical zoning of garnet end-members, typically almandine (Fe), grossular (Ca), pyrope (Mg), and spessartine (Mn). Zoning may reflect prograde growth if temperatures remain below 750 °C, or retrograde overprinting if higher. Whether prograde or retrograde zoning is preserved depends on the extent of diffusion, as temperatures above 750 °C promote diffusion that can erase prograde zonation, resulting in preservation of only retrograde end-member fractions. Diffusion in garnet is multi-component, with the mobility of each end-member influenced by the diffusivities and fractions of the others.

Here, we present a multi-component diffusion model implemented in *underworld3*, coupled with a garnet growth model using end-member fractions obtained from *MAGEMin*, to constrain the pressure–temperature–time (P – T – t) evolution of the southern Western Gneiss Region, Norway. Garnet grains from the Vardehia eclogite record near-isothermal burial between 9.5 and 15 kbar at approximately 545 °C, as indicated by overlapping isopleths from each end-member. Peak conditions reached ~23 kbar and 680 °C, constrained by the peak mineral assemblage. The eclogite subsequently underwent near-isothermal exhumation over ~10 Myr, with temperatures remaining below 700 °C to preserve the garnet end-member zoning from core to rim. Final cooling occurred at ~10 °C/Myr, consistent with U–Pb titanite ages (405–385 Ma) and its closure temperature of ~600–700 °C. Our results are consistent with previous studies showing a progressive decrease in pressure and temperature from north to south, and our inferred P – T path agrees with numerical models of slab break-off driven by continental collision. Future work will combine diffusion in garnet with diffusion, decay, and ingrowth in other elements and minerals to further constrain the complete P – T – t evolution.

O27.10

Multi-mineral geochronology as a means of understanding polyorogenic evolution: in situ Lu-Hf and Rb-Sr applied to the Ilimantsi Greenstone Belt, eastern Finland

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The Ilimantsi Greenstone Belt of the Archean Karelian Province in eastern Finland records amphibolite facies metamorphism at 2.66-2.62 Ga with a later overprint at 1.84 Ga based on resetting of monazite ages (Hölttä et al. 2017). The Hattu Schist Belt occurs within the Ilimantsi Greenstone Belt and is host to Archean orogenic gold deposits including the Hosko gold deposit. Two samples from the Hosko gold deposit were dated by in situ garnet Lu-Hf. In mineralised sediments, garnet associated with vein quartz produced a date of 1837 ± 16 Ma. Rb-Sr in muscovite from the same sample produced a date of 1790 ± 43 Ma. Garnet in a granitic vein cross-cutting the gold hosting sediments gave a date of 2620 ± 24 Ma. This sample clearly recorded a resetting event with younger dates obtained from the rim. Mineral chemistry also indicates distinct compositional differences between core and rim garnet and white mica associated with garnet also contains clear cores and rims based on Si and Mg content. Rb-Sr applied to the zoned muscovite produced a range of dates with an isochron of 2465 ± 38 and MSWD of 84. If these analyses are separated based on Mg content, a range of Archean populations are apparent from 2580 to 2420 Ma. The points with the highest Mg, which target grain rims produce an isochron of 1782 ± 31 Ma. Garnet P-T modelling indicates conditions of at least 450 °C and 2 kbar during growth of garnet rims. Existing K-Ar data from the Ilimantsi region indicate ages of ca. 1.8 Ga for biotite and 2.7 to 1.9 Ga for hornblende (Kontinen et al. 1992). This is consistent with our results, suggesting a >400°C (biotite closure T) but less than 600 °C (hornblende closure T) conditions for the 1.8 Ga event.

The results presented here indicate that the Svecofennian had a larger role in reworking mineralisation at slightly higher P-T conditions than previously thought (i.e. Molnár et al. 2016).

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O27.11

Characterization of the Rb-Sr geochronological behaviour of Li- rich micas

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The Rb–Sr isotopic system in micas is a key tool for deciphering the timing of deformation, cooling, and fluid interaction in metamorphic and magmatic settings. Muscovite typically preserves robust Rb–Sr ages owing to its relatively high closure temperature, while biotite is well known to lose Sr more readily and thus records younger overprinting events and/or helps restoring the cooling history. This difference is generally attributed to structural and crystal-chemical controls: muscovite's Al-dominated dioctahedral sheets yield stronger interlayer bonding and reduced diffusivity, whereas the trioctahedral nature of biotite creates wider interlayers that facilitate easier cation mobility (Dahl 1996).

Despite this broad understanding, the effect of lithium substitution in muscovite on Rb–Sr systematics is poorly constrained. The muscovite-polyolithionite series found in evolved LCT pegmatites progressively approach a trioctahedral configuration as Li^+ fills octahedral sites otherwise vacant or occupied by Al^{3+} in dioctahedral muscovite. This structural transition suggests that Li enrichment may increase susceptibility to Ar diffusion and lower the Ar–Ar closure temperatures (Smith et al. 2005). Yet, systematic studies quantifying how Rb–Sr retention varies across the di–trioctahedral continuum in Li-bearing micas are lacking.

We are investigating this knowledge gap by combining structural characterization of micas with varying Li content and in situ dating of the same crystals using the methods of Rösel & Zack (2022). The analyses are performed with LA-ICP-MS/MS, which allows simultaneous measurement of isotopes for dating as well as major and trace elements (including Li, which cannot be quantified by electron microprobe) for mineral formula calculation. The aim is to establish whether increasing Li content induces predictable changes in Rb–Sr closure behaviour, and to further the understanding of ages obtained from Li-rich white micas.

Addressing this gap will not only improve our understanding of isotopic systematics in different mica crystal chemistries but also contribute to reconstructing the evolution of pegmatite-bearing terranes. It would further provide a practical alternative for dating highly fractionated LCT pegmatites. These pegmatites remain difficult to date accurately with existing methods, yet their significance continues to grow as an important source of lithium for a green energy future.

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First in situ Rb–Sr biotite ages applied to the post-orogenic evolution of the Fennoscandian Shield

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A low closure temperature (300°C), and the high mobility of Rb and Sr in fluid-rich environments, makes the Rb–Sr isotopic system uniquely suited to recording low-temperature events such as exhumation, fluid flow, and late-stage deformation. These processes often go undetected by more commonly used high-temperature geochronometers, such as U–Pb in monazite and zircon, and Sm–Nd and Lu–Hf in garnet, which primarily capture information about metamorphism and magmatic crystallization. Whole-rock Rb–Sr dating has historically been applied to Finnish magmatic rocks (e.g., Vidal et al. 1980; Welin et al. 1983), but this technique is poorly suited for rocks with complex polymetamorphic histories. This is because the whole-rock approach integrates the composition of all Rb- and Sr-bearing minerals in the sample, many of which formed or were compositionally altered during different metamorphic episodes. In situ Rb–Sr dating overcomes these limitations by targeting individual mineral crystals—such as biotite—while retaining information about the mineral’s microstructural context.

This study presents the first application of in situ Rb–Sr biotite geochronology to metasedimentary rocks in Finland. Archean bedrock in the Tuntsa region was extensively reworked during the Paleoproterozoic Svecofennian Orogeny, when Proterozoic rocks were thrust over the Archean basement, leading to crustal thickening and widespread amphibolite-facies metamorphism (1.84–1.79 Ga, 8 kbar at 650°C; Hölttä et al. 2020). Subsequent uplift and cooling of these mid-crustal rocks is evidenced by the partial breakdown of garnet and staurolite to cordierite and, locally, andalusite; however, aside from ca. 1.80 Ga monazite hosted within the cordierite (Hölttä et al. 2020), the timing and rate of exhumation has been largely unconstrained. Preliminary Rb–Sr ages from two generations of biotite in the Tuntsa Suite provide new evidence for < 1.7 Ga cooling, and contribute to a more detailed understanding of the post-orogenic, late Paleoproterozoic to Mesoproterozoic evolution of the northern Fennoscandian Shield.

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Kinematics and Timing of Nappe Stacking in the Olympos-Ossa Region, Greece

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The Hellenic orogen is a crustal-scale orogenic wedge formed during Late Mesozoic–Cenozoic subduction of Africa-derived continental fragments beneath Eurasia. It comprises several palaeogeological zones that were successively thrust over one another. A key tectonic unit in this system is the Cycladic Blueschist Unit (CBU), which records Eocene–Oligocene subduction-related high-pressure/low-temperature (HP/LT) metamorphism followed by retrograde greenschist- to amphibolite-facies overprinting during exhumation. Although widely studied in the Cyclades archipelago, post-orogenic extension and partial submergence since the Miocene obscure the overall structural geometry of the CBU, and the mechanisms and timing of large-scale exhumation remain debated.

The Olympos–Ossa region of northern Greece forms an antiformal dome exposing a continuous section through the main tectonic units of the Hellenic Orogen, including the CBU and its over- and underlying units. This region offers a rare opportunity to reconstruct the deformation and exhumation history of the CBU, and to link mainland Greece with the Cyclades in paleogeographic reconstructions. However, this region has received far less attention than the Cyclades, and its deformation and metamorphic records are only loosely constrained.

Here, we present a new structural map, cross-sections, and fifteen Rb–Sr multimineral ages to constrain the sequence and timing of nappe emplacement and metamorphic overprinting. The study area preserves an imbricated nappe stack of four tectonic units, from top to bottom, the Eohellenic Unit, Pelagonian Unit, the CBU, and the Basal Unit. Integrated structural, petrological, and geochronological analyses show that the Pelagonian Unit, the CBU, and the Basal Unit record successive Eocene–Oligocene HP overprints. Four deformation stages are distinguished: D1 (Pre-Tertiary): top-to-the-SW thrusting of the Eohellenic Unit onto the Pelagonian Unit, under greenschist to amphibolite facies conditions; D2 (48–41 Ma): subduction of the CBU and parts of the Pelagonian Unit, with blueschist-facies overprinting and SW-directed nappe emplacement; D3 (36–28 Ma): thrusting of the CBU onto the Basal Unit, with pumpellyite–lawsonite facies metamorphism in the latter; D4 (from ~23 Ma): NE-dipping extensional faulting responsible for the final exhumation of the nappe stack.

Regionally,

- (1) the CBU in Olympos–Ossa region correlates with the Middle-CBU nappe in the Cyclades based on comparable metamorphic ages;
- (2) syn-orogenic exhumation of the CBU occurred by ductile extrusion within an overall contractional setting, coeval with Oligocene subduction of the Basal Unit. The tectonic extrusion wedge was bounded by a normal detachment above and an out-of-sequence thrust below that operated contemporaneously;
- (3) later exhumation was facilitated by Miocene post-orogenic extension along NE-dipping normal faults, synchronous with Aegean-wide slab rollback and opening of the Aegean Sea basin.

O28.1

A reflection seismic investigation of Söderfjärden, an impact crater in western Finland

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Söderfjärden impact structure (N63°00.6', E21°35.5') in western Finland, is a 6.6-km wide crater. It was formed in early Cambrian period. It is a well-preserved meteorite crater with the rim largely preserved and it's filled with lower and middle Cambrian sediments, up to the level of the crater depression of the central uplift. From previous drilling the Quaternary sediment thickness is between 30–75 meters. Thick Quaternary deposits bury the central uplift and the Cambrian sediments. To explore the crater floor the top of the impactites (the base of the sedimentary infill) in the ring depression, drilling and geophysical methods are the two possibilities. The inner structure of the crater was studied by two profiles of reflection seismics, one short profile above the central uplift and one longer profile in the eastern part of the crater above the ring depression. The deepest part of the crater bottom lies in the eastern part of the ring depression and is suggested to be 330–410 m in depth. The top of the impactites is interpreted to be discontinues with the Cambrian sedimentary infill on top. This transition appears to be jagged. The thickness of the Quaternary and Holocene layers was interpreted to be 89–96 m in the location of the long profile, deeper than the 75 m which is based on the previous drillings. This discrepancy might be caused by that the area of the central uplift probably was slightly elevated relative to the surrounding ring depression during the deposition. The reflectors in the Cambrian sediments are close to horizontal, compared with the Quaternary sequence that is more irregular. The depth to the central uplift beneath the short profile was 36–46 m and faults could be observed within the central uplift.

O28.2

Compositions and ages of mare and highlands impact glasses in Apollo 11 soil

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Impact glasses in the lunar regolith carry unique information about surface processes, terranes, and element fractionation during impacts, complementing information about magmatic processes derived from volcanic glass beads and rock samples. Here we present major and trace element data, and U-Th-Pb isotopic compositions of impact glasses that define diverse source rocks sampled by impacts, accompanying element fractionation, and the timing of impact events on the Moon.

Chemical compositions of the 223 glass spherules (75-250 μm) were classified as mare or highlands based on their major element ratios (Zeigler et al. 2006). All of these are interpreted as of impact origin. Mare glasses comprise ~86% of the studied particles reflecting the geological setting of the Apollo 11 landing site. However, only 10 of these have the high-TiO₂ (>6 wt.%) low-Al₂O₃ (<11 wt.%) compositions typical for Apollo 11 basalts (Neal & Taylor 1992). Most of the mare glasses have compositions corresponding to mixtures of basaltic, highlands and K-, REE-, P-rich (KREEP) material forming a continuous trend from basaltic towards highlands compositions. This is consistent with a predominantly regolith source considering that previous studies have found that the Apollo 11 regolith represents a mixture of 66% mare basalt, 20% feldspathic highlands material and 8% of a KREEP-rich component (Korotev & Gillis 2001).

Both groups exhibit a systematic depletion in moderately volatile lithophile elements (Na, K, and Si and trace elements, e.g., Rb), which is probably related to impact conditions. Many of the depleted glasses also have elevated Th/U ratios (5-14 in mare glasses and 8-14 in highlands glasses), possibly reflecting U volatility during impacts. The high-Ti, low-Al mare glasses with local basalt affinities are not volatile-depleted, suggesting provenance from modest-size local impacts.

The volatile-depleted glasses are characterized by consistently lower U-Pb ages with 60% of them having ages <150 Ma and 19% of them having ages between 150 and 500 Ma. Young U-Pb ages (< 1 Ga) were also reported for glasses mostly formed in impact craters of 1-5 km in diameter from Chang'e 5 soil (Long et al. 2022). This may suggest that even modest impacts can produce significant depletions of moderately volatile elements, producing a clearer geochronologic record of the impact history of the Moon.

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O28.3

The Lieksa and Löpönvaara meteorites: unique discoveries from eastern Finland

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On May 30, 2017, a small rust-covered, heavy rock was discovered from the ground in Löpönvaara, Lieksa, eastern Finland. The rock was examined at the Geological Survey of Finland soon after and confirmed to have a meteoritic origin. During the following months, several other small, suspected meteorites were discovered from the area, and at present, the total number of finds is over 100. So far, only two of these finds have been named, classified, and characterised; the Lieksa pallasite (Chiappe et al. 2023) and the Löpönvaara iron (Kotomaa et al. 2025). Both of these meteorites are ‘*ungrouped*’, meaning that they are mineralogically and chemically unique and defy classification into the existing pallasite and iron meteorite subgroups. The Lieksa pallasite contains ~80 vol% metal (kamacite; α [FeNi], and taenite; γ [FeNi]) and ~20 vol% olivine, chromite, and pyroxene inclusions, with minor troilite (FeS; Chiappe et al. 2023). In contrast, the Löpönvaara iron contains ~75 vol% metal (kamacite) and ~22 vol% schreibersite ($[\text{Fe,Ni}]_3\text{P}$), with minor troilite inclusions (Kotomaa et al. 2025). The two meteorites also have distinct trace element compositions. Other suspected meteorites discovered from the area have very unequilibrated textures and contain mainly iron, with varying amounts of olivine, troilite, pyroxene, and schreibersite, but their trace element or isotopic fingerprints have not yet been established.

So far, only Lieksa has been analysed for isotopic composition (Mo, Ru, W, Os, and Pt), and the data indicate that the meteorite originates from a previously unsampled NC-type parent body (Chiappe et al. 2023). The unusual mineral and major element composition of the Löpönvaara iron suggests melt immiscibility, but the textural features of the meteorite suggest impact-related origin. The discovery of additional multiple small meteorites with similar mineralogies and textures in a relatively small area indicates that these samples might have a shared origin in a highly heterogeneous parent body with an impact-related origin.

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O28.4

Impactites from Kitkiöjärvi, northern Sweden: Mineralogical evidence of a meteorite impact

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Impact structures are vital archives of planetary processes, yet erosion and sedimentary cover hamper the detection of many ancient craters. An integrated study of impactite cobbles from glaciofluvial sediments in three gravel quarries at the Kitkiöjärvi, northern Sweden, provides new insights into a ‘lurking in the shadows’ impact structure. Since the first discovery of impactite erratics (Kreitsmann et al. 2018), fieldwork in 2023–2025 has yielded >70 samples, 25 of which underwent mineralogical and petrophysical analyses, along with evaluation of potential source structures. The results refine the characterisation of impact melt rocks linked to the 658.9 ± 6.9 Ma (Cryogenian) event (Alwmark et al. 2024).

The Kitkiöjärvi samples fall into three groups: (i) impact melt rocks, (ii) lithic breccias, and (iii) fractured target rocks. Only the melt rocks carry planar deformation features (PDFs): 74 sets were identified in 36 quartz grains. Of these, 70 oriented along rational crystallographic orientations parallel to {10I3}, {10I4}, and {10I2}, indicating a higher end of shock metamorphism. Melt rocks commonly display fluidal textures and contain rare glassy melt and granitic clasts. Lithic breccias consist of angular lithic fragments in a fine-grained matrix, while the fractured target rocks serve as a petrological reference. Physical property measurements distinguish the impactites from regional lithologies. Impactites have higher porosities, and impact melt rocks show moderate magnetic susceptibilities (avg. 0.006 SI) compared to target rocks (avg. 0.002 SI). Induced magnetisation dominates over remanence in all lithologies.

Impactites in sandy gravel imply deposition via meltwater processes, possibly concentrating boulders from distal sources. Regional Quaternary data indicate complex transport from NW to SW along palaeo-glacial flowlines defined by drumlins, moraines, and drainage patterns. Although several crater candidates exist, the exact source of the impactites remains unknown. Future work will combine geophysics and field mapping to refine the search.

Acknowledgments

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O29.1

Active geophysical and geological measurements of permafrost peatlands in the Peera palsa mire, in the Kilpisjärvi area, Northwestern Finland

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Palsa mires are unique landforms of subarctic areas in the Northern Hemisphere. Palsas are permafrost peatlands with palsa mounds rising above the surface of the mire with ice-rich permafrost cores and peat cover (Seppälä 1986, 1988). Palsas are highly sensitive to climatic variability and serve as important indicators of permafrost change. Inspired by recent studies of palsa mires in Finland (Verdonen et al. 2023; Leppiniemi 2025) we conducted field survey in the Peera palsa mire in the Kilpisjärvi area, the most Northwestern Finland with suitable geophysical and geological methods involved.

The field survey was taken place at August 2025 in the Peera palsa mire where we measured seven 2D resistivity profiles with corresponding ground penetrating radar profiles and collected a comprehensive assortment of geological samples of the peat around the ice lenses, from the top of the mound all the way to the bottom layer before the mineral soil. We also have drone data (LiDAR, multispectral and thermal) available from the time of the field campaign measured by University of Eastern Finland.

The aim of this field campaign was to measure the thickness of the active layer, study the geological properties of the peat and to gain knowledge about the vertical and horizontal dimensions of the permafrost core inside of the palsa mound. This research provides the foundation for tracking future changes of the Peera palsa morphology and extent with these methods.

Due to the sharp contrasts in electrical resistivity and dielectric permittivity between the ice-lenses and the surrounding peat, we managed to achieve models containing the active layer and the ice-lenses of the palsa. Our results give great insights about the suitability of these methods for the palsa mire studies and give suggestions for improvement related to possible future measurements.

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O29.2

Building a Stratigraphic Reference for the Eocene–Oligocene of the NE Atlantic: Insights from the U1572B Hole on the Vøring Marginal High

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The Eocene–Oligocene transition (EOT) was a turning point in Earth’s history, associated with the shift from greenhouse to icehouse conditions. In the NE Atlantic, late Paleocene–early Eocene continental breakup and resulting bathymetric changes reshaped global ocean circulation and drove major environmental transformations. However, characterizing high-latitude EOT stratigraphy has remained challenging for several reasons. These include 1) key intervals are often truncated by unconformities, 2) often low sampling resolution has been undertaken over this interval, 3) frequent barren microfossil intervals, and 4) incomplete magnetostratigraphic records. As a result, the Norwegian–Greenland Sea stratigraphy is less well constrained than sites at lower latitudes.

IODP Expedition 396 Hole U1572B, located on the Vøring Marginal High, offers a unique opportunity to overcome these challenges and to study the Eocene–Oligocene interval in detail. Its near-complete recovery, rich dinocyst assemblages, and integration with an extensive seismic dataset offer a solid basis for refining biostratigraphy and strengthening correlations across the NE Atlantic. In this study, we combine high-resolution dinocyst biostratigraphy (20–50 cm sampling) across a ~100 m thick Eocene-lower Oligocene interval with paleomagnetic analysis, calibrating magnetic chrons using both onboard core pass-through track measurements and over 100 discrete samples. Continuous XRF core scanning at 3 cm resolution is used to study elemental variations across key stratigraphic boundaries in the interval.

Paleomagnetic analysis of borehole U1572B reveals a strong and coherent magnetic signal throughout the recovered interval. In the early Eocene, the Azolla phase is clearly associated with the C22n–C21r reversal and the Ypresian–Lutetian transition. Magnetic chrons can be confidently assigned up to the middle Eocene (Lutetian), whereas the late Eocene interval (Priabonian–Bartonian) is less well constrained due to minor unconformities and less well preserved dinocyst assemblages. Yet, significantly, an earliest Oligocene (Rupelian) record spanning chrons C13r to C12n is identified, sandwiched between unconformities preliminary dated as middle Priabonian and upper Burdigalian. XRF core scanning highlights pronounced elemental variations: ash-rich layers display elevated K/Al ratios and increased magnetic susceptibility, specifically in the middle Eocene interval, while biosiliceous intervals and claystones in the upper Eocene display elevated Si/Al ratios. Ratios of Ti/Ca, Fe/Ca, and K/Ca indicate variations in terrigenous input, with elevated values during the EOT, reflecting enhanced sediment influx driven by regional glaciation and uplift, and potentially correlating with the Oi-1 event.

IODP Hole U1572B provides a reference section for the Eocene–Oligocene in the NE Atlantic, establishing a framework that will support robust stratigraphic correlations in high-latitudes for decades to come.

O29.3

Short-term cold bottom water temperatures during thermal maxima?

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Marine temperatures in the subpolar northern hemisphere saw significant deviations from global records during the early- to mid- Paleogene, both in ocean bottom waters and at the sea surface. Refined absolute and relative age data for ashes and glendonite carbonate are used in conjunction with quantitative temperature and environmental reconstructions to revise the timing, duration and magnitude of cool episodes within this greenhouse to hothouse period.

O29.4 (Keynote)

Reassessment of the Carnian Pluvial Episode: Timing, Duration and Impact

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The Carnian Pluvial Episode (CPE) marks a major global climatic shift from arid to humid conditions, triggering profound environmental and biotic changes. It is often regarded as the dawn of modern ecosystems, foreshadowing the rise of the dinosaurs and major turnovers in both marine and terrestrial life. This climatic transition is thought to have been driven by disturbances in the global carbon cycle, linked to the emplacement of the Wrangellian Terrane Large Igneous Province (WT-LIP) in the northern Panthalassic Ocean (~231–225 Ma). Despite its significance, detailed studies connecting the CPE to Wrangellia through geochemical evidence remain limited, largely due to poor chronostratigraphic constraints on both Wrangellia and the sedimentary record of the episode. Here, we present high-resolution geochemical data—including carbon isotopes, elemental variability, weathering indicators, and Hg/TOC ratios—integrated with lithological descriptions, from the Carnian Knocksoghey Formation sampled in the Carnduff-2 core, Northern Ireland, UK to evaluate the temporal link between the emplacement of the WT-LIP and the onset and pulses of the CPE. The Knocksoghey Formation represents continental sediments that show an abrupt shift to coarse-grained siliciclastics at the presumed onset of the CPE, which, here, helps assessing the definition of the CPE as well as examining the duration and timing of the event globally with a particular emphasis on how perturbations to the carbon cycle correspond to climatic responses such as increased siliciclastic deposition.

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O29.5

Volcanic proxies across the Permian-Triassic boundary in Svalbard: Evidence of sporadic Siberian Traps activity

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The End Permian Mass Extinction (EPME; 251.9 Ma) is the largest environmental crisis in the Phanerozoic, with more than 80% of marine species and around 75% of terrestrial species wiped out across a short (<100 kyr) time frame. The EPME is coincident with the emplacement of the Siberian Traps large igneous province, suggesting a possible causal relationship through greenhouse degassing from magmatic and thermogenic (contact metamorphism) sources. However, the timing, style, and fluxes of Siberian Traps activity can be better constrained. We investigated three boreholes and one outcrop from Svalbard and the Barents Sea, which were all part of a semi-enclosed epicontinental sea on the northern margin of the Pangean supercontinent at the time. These sites lie within the 'Goldilocks Zone': near enough to record numerous volcanic proxies including ash layers, yet distal enough (1500 – 2500 km) from the Siberian Traps not to be swamped by the magmatic signal. We use mercury (Hg) enrichments along with carbon ($\delta^{13}\text{C}$) and osmium ($^{188}\text{Os}/^{187}\text{Os}$) isotopes to constrain peaks in volcanic and magmatic activity with respect to the environmental disturbances across the Permian-Triassic boundary. Significant variations in these proxies are interpreted to reflect pulsed Siberian Traps activity, with possible evidence of a more enclosed basin from the Panthalassic Ocean than current plate reconstructions suggest. These findings can be tied to biomarker and radiometric age constraints for the EPME to improve the relative and absolute chronologies for both the extinction event and the peak in Siberian Traps activity.

P29.1

Atmospheric pressure recorded by mid-Miocene basalts in eastern Iceland

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Very little is known about Earth's atmospheric pressure prior to historical records from the 1600s, although it is generally assumed that there were no significant variations throughout the Phanerozoic (539 Ma to present). However, recent advancements in our understanding of atmospheric erosion processes have underscored the importance of investigating paleoclimate records in the geological archive. One promising method for estimating ancient atmospheric pressure involves analyzing the size and distribution of air bubbles trapped within thin basalts (i.e. vesicle paleobarometry), but this technique has not yet been widely utilized.

Iceland presents a unique opportunity for such research, as its extensive lava formations could provide insights into Arctic atmospheric conditions over the past 15 Ma. We present the results of a pilot study from ten mid-Miocene (ca. 14-12 Ma) lava flows around Seyðisfjörður (eastern Iceland), as well as one upper Pleistocene (< 0.8 Ma) flow from the Reykjanes peninsula. We aim to contribute to a deeper understanding of Earth's atmospheric pressure variations and their implications for paleoclimate science.

O31.1 (Keynote)

Ice streams of the Eurasian Ice Sheet Complex

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Accurate projection of ice sheet contribution to future sea-level rise requires uncovering the long-term dynamics of fast-flowing ice streams; the primary conduits of meltwater to the ocean. Contemporary observations of ice sheet surface changes indicate that ice streams exhibit variability in speed and can switch on-and-off over time. However such observations only cover the last few decades, insufficient time to capture all glacial processes. Further, direct observations from present-day ice stream beds are limited to spatially-restricted insights into subglacial processes and conditions influencing fast-ice flow. Geological records spanning the last glacial cycle (10,000s of years) provide evidence of the nature of, and spatial variations in, subglacial conditions and instances of fast-ice flow across ice sheet beds. Based on varied evidence numerous fast ice flow pathways are postulated to have existed within the former Eurasian Ice Sheet Complex (EISC), including both marine-terminating ice streams and outlet glaciers of various sizes, and terrestrially-terminating 'ice-lobes'. These interpretations have accrued alongside changes in conceptual understanding of ice stream dynamics and development of robust criteria for identifying fast ice flow in the geological record (e.g., Stokes & Clark 1999). Together with increasingly widespread availability of high-resolution (1-10 m) marine and terrestrial data that facilitates digital mapping of former ice sheet beds. Here, we conduct a comprehensive review of postulated fast-flow pathways of the EISC. This new digital synthesis provides i) an opportunity to examine and assess variations in geological signatures of fast ice flow from both marine and terrestrial ice sheet sectors, ii) assessment of the prevalence of ice streaming within the overall ice flow configuration and evolution of the EISC, and iii) updated and revised constraints on the spatial occurrence of ice streams within the EISC for palaeo-glaciological modelling.

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O31.2

Almost 1 km deep iceberg scours on the newly discovered Atlantic Dana Seamount (71°40'N, 15°W), Greenland Sea, Arctic Ocean

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Iceberg scours are created by drifting icebergs that plough into the seafloor with their keels. These prominent geomorphic features are widespread in the Arctic and provide critical insights into past ice-sheet dynamics and ocean circulation. At local scales, iceberg scours influence benthic ecosystems, pose risks to offshore seafloor infrastructure, and can trigger submarine landslides. Here, we report on multibeam echosounder and subbottom profiler data from the 2025 AOC cruise on R/V Dana that document iceberg scours from the newly discovered Atlantic Dana seamount (71°40'N, 15°W) in more than 975 m of water. Semi-automated mapping of 212 iceberg scours shows that they are predominantly oriented in northeast-southwest direction. Iceberg scours occur in two clusters around 810 m and 860 m water depth and are on typically ~20 m deep, 330 m wide, and >2 km long. The longest iceberg scour is more than 10 km long and more than 60 m deep, crossing the entire seamount. One scour terminates in a landslide scar, documenting that icebergs can be geohazards hundreds of kilometers away from their source. Sediment core data from the top of the seamount are currently investigated and will give rise on the timing of iceberg scouring. Given the large water depths in which we find iceberg scours, we attribute them to giant paleo-icebergs that were more than 1 km thick. The absence of parallel lineations speak against a grounded iceshelf this far south in the North Atlantic. We conclude that these scours are formed by individual icebergs that probably came from a calving front at the Northeast Greenland shelf edge or migrated from the Arctic Ocean southward through the Fram Strait during past glacial maxima.

031.3

Early Holocene deglaciation of eastern Iceland from cosmogenic ^{36}Cl exposure ages and tephrochronology

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The recessional history and dynamics of the Icelandic Ice Sheet (IIS) during the past glacial-interglacial transition provide valuable long-term context for records of recent environmental changes in high northern latitudes that document accelerating ice retreat in response to warming climate. In addition, numerical modelling of ice sheet geometry and behaviour requires reliable and detailed geochronologic data on changes in ice configurations and limits. The IIS presumably extended to the shelf break at the Last Glacial Maximum and then collapsed and retreated to a position inside the present-day coast during the Bølling-Allerød interstadial. Following the Younger Dryas and Preboreal readvances to coastal areas, the IIS actively retreated inland and deposited multiple end moraines of unknown age. Remnants of the IIS were smaller than present glaciers by ~9 ka BP. Despite this broad framework of glacial events in Iceland, large gaps remain in the detailed timing and rates of ice sheet recession.

We provide constraints on the timing, pattern, and rate of deglaciation from coastal areas to the interior highlands with ^{36}Cl exposure dating and tephrochronology. Roughly 30 samples for ^{36}Cl exposure dating were collected from prominent moraines, perched erratics, and ice-scoured bedrock along the track of a palaeo-ice stream in NE-Iceland extending from Vopnafjörður to Vatnajökull. A subset of these samples reveals decreasing exposure ages upice along the center flow line of the ice stream and a rapid deglaciation of the IIS during the Early Holocene. Samples near the coast in Vopnafjörður fall within the Younger Dryas and provisional ages of erratics at Bustarfell suggest inland ice retreat shortly thereafter. ^{36}Cl ages the Skessugarður and Fiskidalur moraines farther inland date to ~11–10 ka, marking ice-sheet still-stands or readvances that punctuated the overall retreat during the Early Holocene. Pending dates from three moraines further inland, along with analyses of tephra marker horizons, will provide additional constraints and shed light on the rates and timing of the final deglaciation.

031.4

Kvarken archipelago rocks – a long duration (a > 100 kyr) short- and long-term glacial erosion test bench in the ice sheet centre

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The burial and erosion histories of ice sheet centres are potentially complex but remain poorly constrained. In this study, we examine the Kvarken archipelago, western Finland, a UNESCO World Heritage site, characterized by very rapid postglacial glacio-isostatic rebound (10 mm/yr) and exceptional assemblages of hard and soft glacial bedforms. Kvarken lay at the former Fennoscandian Ice Sheet centre at the Last Glacial Maximum. Previous work has focused on the final deglaciation at 10.7-10.5 ka when a < 400 yr long phase of intense subglacial activity began, with abrupt switching of ice flow in the retreating ice margin, producing new striation arrays, widespread erosion of till and bedrock, overpressured conditions along meltwater corridors, and the formation of new soft bedforms. We focus here on earlier events over the previous ~100 kyr and, particularly, the emerging picture of ice sheet burial, shielding by fresh and salt water, episodic till cover, and slow average erosion, punctuated by brief pulses of bedrock quarrying and what this may mean for cosmogenic nuclide sampling campaigns in this and other former ice centres.

The Kvarken event stratigraphy is consistent with that of the wider Ostrobothnian region. During the Late Saalian glaciation, the ice divide was positioned further north, glaciers flowed through the Kvarken as a broader ice stream, sculpting roche moutonnées, whalebacks, and scours. This significant phase of glacial erosion was not replicated by MIS 4 and MIS 3/2 ice sheets – Saalian till and MIS 5 organic sediments survived in bedrock depressions. A dataset of 1100 measurements of individual striations taken on Precambrian gneiss and granite bedrock surfaces around present shorelines includes multiple sets of crossing striations found on single rock bumps. The implication is that overall downwearing on rock bumps by post-Saalian glacial abrasion was < 0.1-0.5 m. Slow erosion is linked to long periods (~100 yr) of ice free conditions, episodic flooding, dominance of non-erosive, cold-based ice covers, episodic protection by till beds, and bed hardness. Rapid glacial erosion appears to be confined to brief periods during ice sheet deglaciation. Kvarken is an attractive target for future cosmogenic nuclide sample campaigns to confirm short- and long-term glacial erosion rates below the ice centre.

031.5

Drifting Geomagnetic poles and polar ice conditions

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The shifting positions of the magnetic north and south poles have played a significant role in polar ice dynamics.

As the magnetic north pole has migrated from the Canadian Arctic toward Siberia over recent decades, its path has intersected with regions of open water during late summer and early autumn. Similarly, the magnetic south pole began shifting from land or solid ice after 2016/2017, whereas this occurred for the magnetic north pole in 2006/2007.

This drift aligns with theories that weak geomagnetic fields—such as those near the poles—can boost water evaporation. Consequently, when open water is close to the magnetic pole during ice minima, evaporation increases, resulting in more low clouds that trap surface heat and limit radiative energy loss to space.

The feedback loops from this process led to local warming at the North Pole after 2006/2007 and the South Pole after 2016/2017. The link between pole movement and changing sea ice patterns suggests a potential geomagnetic effect on polar climate and ice.

Reduced ice coverage in the southern hemisphere has been observed in 2023 and 2024, as the magnetic pole moved farther over open waters.

Comparing ice coverage across both hemispheres shows a link between magnetic pole positions, evaporation, and ice dynamics. March and September data reveal that magnetic pole locations, evaporation, and cloud formation significantly affect ice development at the poles.

The magnetic north pole has shifted steadily east-northeast by over 50 km annually since 2000. If this continues, it will reach Siberia within a decade. Continental regions, lacking surface water for evaporation and cloud formation, experience cooler temperatures, less cloud cover, and increased sea ice when the pole moves over land instead of ocean.

The southern magnetic pole is moving and may soon be over open ocean, which could cause local warming in the southern hemisphere.

The effects of future northern hemisphere cooling and southern hemisphere warming are uncertain. Accurate monitoring and reliable models are crucial to determine if these changes will occur and how they might affect global climate. The significance of this effect in polar regions is still debated, and more research is needed to clarify its impact on polar climate trends.

031.6

Alpine Ice Sheet dynamics drive continental-hemispheric scale dust events: Age and provenance of last glacial loess in central Europe

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Last glacial Greenland ice cores record that cold climate events (stadials) were associated with greatly enhanced atmospheric dust activity. Detailed radiocarbon dating from loess in Hungary, central Europe demonstrates concurrent increases in dust activity in dust emitting regions. Yet, the causes of these coupled changes in last glacial dust and climate and the role of dust in rapid climate change remain unclear. Here we address this gap through multi-proxy source analysis (detrital zircon U-Pb ages, heavy mineral assemblages, garnet chemistry and quartz grain morphology) of the previously radiocarbon dated loess in Hungary. We show that loess-dust particles were dominantly produced by subglacial grinding processes in the eastern Alps. Particles were released along with stadial Alpine Ice Sheet-driven meltwater pulses, turning major river systems draining the Alps into efficient but intermittent sources for dust deflation and loess deposition in Europe. During the LGM, strengthened anticyclonic circulation potentially facilitated wider dispersal of Alpine Ice Sheet-produced dust to source distal regions as far as Greenland. We propose that resultant continental-hemispheric scale changes in atmospheric dust loading amplified concomitant North Atlantic climate cooling and ice sheet decay during Greenland stadials.

O31.7

Joint luminescence and radiocarbon dating of Holocene fire history and dune activity in Arctic Fennoscandia

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Aeolian parabolic dunes in Arctic Fennoscandia are widely scattered across diverse biomes, from tundra to mountain birch and pine forest. Many of these dunes show signs of current degradation or recent partial activity, and numerous buried soil, charcoal and sand layers demonstrate that dune stability is repeatedly interrupted by fire events and dune reworking episodes during the Holocene. As such, these systems have great potential as archives of Arctic landscape, climate and fire history in a highly sensitive environment, and over a range of biomes. However, few of these dunes, especially in Sweden, have been analysed using modern luminescence and radiocarbon techniques to constrain the timing of the dune stability, fire and reworking events. The result is that we have a) limited understanding of whether fire frequency or landscape degradation/dune mobility episodes have changed over the Holocene, b) whether there are wider patterns in these events over Arctic Fennoscandia, and c) if so, what the climatic or anthropogenic drivers of such changes may be.

Luminescence dating of aeolian sands constrains the timing of dune sand movement, allowing direct dating of reworking events, while radiocarbon dating of charcoal constrains the timing of fires that may have marked the end of periods of stability, and the initiation of dune degradation and reworking.

Here we apply detailed quartz optical stimulated luminescence (OSL) and feldspar post infrared - infrared stimulated luminescence (pIR-IRSL) dating to multiple dunes in Arctic Sweden and Finland over a diverse range of biomes. We also apply detailed AMS ¹⁴C dating to charcoal fragments from charcoal bands exposed in the stratigraphy of these dunes, which often separate dune reactivation sand units. In this way, not only can we cross-check multiple independent chronological techniques, but we can also construct detailed local dune development and reworking histories across a wide area of Arctic Europe. Combining these histories allows testing of potential wider climatic and human drivers for fire and landscape changes in Arctic Fennoscandia over the Holocene. Our detailed, multi-technique approach reveals substantial differences in these histories across biome type and location. Despite these differences, some wider trends are also apparent, notably a substantial increase in fire and dune activity after the Holocene Optimum and in recent centuries.

O31.8

Late Holocene shoreline displacement and storminess in the Harilaid Peninsula, NW Saaremaa Island

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The Harilaid Peninsula (NW Saaremaa I.) is a low-lying coastal landform (~4 km², up to 4.7 m a.s.l.) bordered by the Baltic Proper, Uudepanga Bay, and Haagi Bay. It evolved from a cluster of islets into a tombolo-connected peninsula, characterized by sandy beach ridges and foredunes in the north, pebbly–gravelly ridges in the south, and a boulder–pebble spit complex (Kelba) in SE (Rivis 2004). The area experiences severe storm conditions with wind speeds reaching 19.7–23 m s⁻¹ (gusts up to 27–33 m s⁻¹) and significant wave heights of 4.4–4.6 m, particularly during October–December (Suursaar et al. 2008), making it one of Estonia's most rapidly changing coastlines and an ideal natural laboratory for storminess research. This study reconstructed Late Holocene shoreline displacement and storm activity by investigating six isolated lake basins at different altitudes. The research integrated cartographic materials, high-resolution LiDAR elevation data, GPR, and multi-proxy sedimentological analyses including loss on ignition, grain size analysis, magnetic susceptibility, X-ray fluorescence geochemistry, computed tomography, and radiocarbon dating. Results indicate that the oldest lake became isolated from the Baltic Sea approximately 1325 AD, driven by glacio-isostatic adjustment and eastward progradation of a coastal spit. The transition from marine to lacustrine conditions is marked by decreased Br/Ti ratios reflecting loss of marine influence. The sediment record preserves three distinct storm events dated to 1320–1370 AD and 1550–1610 AD, and one prolonged period from 1730–1970 AD that corresponds with historical storm chronologies. Pre-isolation storm deposits consist of fine sands from reworked coastal bars, while post-isolation storm layers contain coarser, medium-grained sands derived from spit barrier erosion and overwash, consistent with modern storm processes observed at Harilaid Ps. These findings demonstrate that isolated coastal lake sediments provide valuable archives for reconstructing centennial-scale storminess patterns and shoreline evolution in the eastern Baltic Sea region.

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031.9

A Giant Paraglacial Paleo-Landslide on the Flank of a Danish Tunnel Valley

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Few scientific studies have documented Danish landslides and giant paleo-landslides remain virtually unexplored (Svennevig et al. 2020). Here we present a pilot study detailing the possible giant landslide 'Nørre Vilstrup' within the Vejle valley (Vejle Ådal) in eastern Jutland, Denmark. The Vejle valley is a tunnel valley incised into a subglacial plateau, with elevations of 80 – 100 m. The area was last glaciated during the Late Weichselian (~25-11.7 ka BP).

Based on 0.4 m LiDAR data, the lobate landform at Nørre Vilstrup exhibits morphological characteristics indicative of a paleo-landslide. The feature has an area of ~7.4 km², measuring ~3 x ~2.3 km and protruding 0.5 km north into the valley. The lobate form contains twelve east–west-oriented linear features, spaced ~120 m apart and with ~7 m of relief, which are absent from the surrounding terrain. Within the proximal (southern) end of the lobate feature, there is a bowl-shaped depression with an area of 1.48 km² and elevation ranging between 31-52 m. To the east and west of the depression, ~27.7 m deep gullies define the southern margin of the lobate landform. It appears to deform the valley fill forming convex accumulation stands that slope back toward the lobate body. Existing airborne Transient Electromagnetic data (SkyTEM: Sørensen et al. 2004) were used to interpret the subsurface conductivity. Co-interpretation of SkyTEM and borehole information indicates the presence of Paleocene clay and Miocene sand layers below Quaternary deposits within Nørre Vilstrup that align with the east-west linear surface fabric.

The internal structure indicates that overpressured Pleistocene clay intruded through sandy deposits via diapirism, likely forming a caldera-like depression at the landslide's proximal end during the event. Subsequent runout to the valley floor could have modified gullies as seen on the eastern flank of the landslide.

The timing of the paleo-landslide is uncertain, but the presence of overpressured clays suggests that failure occurred soon after glacial ice retreat. Evidence of diapirism points to a sudden failure. The deformed valley fill forming stands at the distal end may represent the slide's toe or result from a "bulldozing" effect, where the valley fill was abruptly pushed outward and upward. These interpretations suggest a high-energy, catastrophic event rather than gradual deformation.

Future work will use new tTEM, resistivity surveys, and boreholes to refine stratigraphy and test the role of mud diapirism. We also aim to better constrain the landslide age from overlying deposits and reworking.

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Late deglaciation, catastrophic floods, rapid uplift, and a stray bear - New observations from northern Sweden

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We report new observations and results concerning the last deglaciation in northern Sweden. Focusing on the timing and retreat pattern of the last ice sheet demise, including the evolution of large ice-dammed lakes and their catastrophic outburst floods, we also present new data on postglacial isostatic adjustment, as well as palaeogenetic evidence of the very first postglacial faunal colonisation.

In northern Sweden, the scarcity of end moraines or other ice-marginal landforms has limited the possibilities to reconstruct the pattern of ice recession. In addition, absolute dating constraints are woefully few, leaving the timing and location of final ice sheet decay still elusive. Here, we show how mapping and dating of deglacial ice-dammed lakes and their drainage routes have offered a solution to these problems.

In the late stages of the deglaciation, extensive glacial lakes were dammed between the easterly retreating Scandinavian Ice Sheet and the Scandinavian mountains to the west. The former existence of ice-dammed lakes has been known for over a century, but almost no absolute dates of the last deglaciation have been reported. Also, in recent years, the advent of LiDAR-based digital terrain models has revealed the Scandinavian landscape at an unprecedented resolution, enabling us to in great detail trace the filling, coalescence, and drainage of ice-dammed lakes along the Scandinavian mountains, and determine their requisite and evolving ice sheet marginal positions. In addition to the pattern of ice-sheet retreat, radiocarbon dating of cored sediments that capture glacial- to nonglacial lake transitions, and also tree trunks (*Pinus sylvestris*) downed by one of the floods, indicate a later final deglaciation than previously thought with sizable ice sheet remnants in northern Sweden as late as c. 9.0 cal. ka BP.

Beyond tracing the ice sheet retreat, the landforms and sediments left by the ice-dammed lakes and their drainages also inform on, e.g., patterns and magnitudes of postglacial isostatic uplift, indicating regression rates of ~2 dm/yr in the early Holocene. Moreover, the glaciolacustrine sediments from former ice-dammed lakes have proven excellent archives preserving genetic information of the first postglacial colonisation, including an ancient brown bear (*Ursus arctos*) environmental genome derived from one single male individual and phylogeographically inconsistent with current postglacial colonisation models. Taken together, these new findings highlight how the diverse glacial landscapes of northern Sweden provide a smorgasbord of Quaternary geological information with much left to be explored!

O31.11

Revisiting fjörumórin in Faxaflói: refining Iceland's Early Holocene low-stand

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The thin, dynamic crust of Iceland is particularly sensitive to the loading and unloading of the land by glaciers and ice sheets. Determining the pattern and rate of postglacial sea level change in Iceland is critical for constraining models of deglaciation, ice sheet behavior, and palaeoclimate. Despite decades of work, relative sea level (RSL) histories remain poorly resolved due to patchy coverage, poorly constrained sea level index points, chronological uncertainties and minimal data from the shallow marine environment. While many of these records can be improved with enhanced geochronological precision today, the largest unknown relates to the sea level low-stands during the deglaciation. This project will compile and quality assess existing data as well as further investigate submerged peat to improve our understanding of relative sea level low-stands. The database will be supplemented with new geochronological (tephra and radiocarbon) data from submerged coastal peatlands located in west Iceland, specifically the classic site of Seltjörn, Gróttu (-4.2 m beneath high tide; Þorarinsson 1956). These findings contribute to our understanding of the deglaciation of the Icelandic Ice Sheet and the Early Holocene sea level low-stand.

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P31.1

A revised highest shoreline database and model for Sweden

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Of all the Quaternary geological boundaries in Sweden, the highest coastline (HC) is arguably the most important. The position of this line in the landscape demarcates the highest water elevation ever reached since deglaciation. In the area above this line, the surface deposits are mainly of glacial or glaci-fluvial origin. Below this line, the landscape is largely reworked by wave action or covered by littoral and/or marine deposition.

During the mid-1800s, the understanding of the assumed 'water level lowering' had shifted to the idea of a land uplift. In 1865, a survey report by Axel Erdman, the first director of SGU, gave a regional view of the HC of Sweden based on mapping of water-lain sediments. Since then, researchers have collected HC observations at more than 1,000 localities. These observations are mainly based on morphological imprints in the landscape or grain-size variations. In the early 2000s, these observations were compiled and modeled into an HC map of Sweden. However, this model was based on a low-resolution DEM, and the localities could not be thoroughly evaluated, due to the almost impossible task of revisiting them all. However, with new, detailed DEMs, these localities can be digitally revisited.

First, all localities were evaluated using detailed DEMs and revised if necessary. Revisions were made if clear morphological evidence was found that could strengthen or rule out the original observation. Original references were reviewed. Localities were given attributes based on the confidence level. The highest level of confidence was set for clear morphological settings, such as delta plains or the upper limit of shorelines/beach ridges. A lower level of confidence was set for localities based on grain size variations, with no clear morphological imprint. If localities were interpreted as not referring to HC (e.g., younger landforms) or if the observations were poorly described, these were marked accordingly and not used in the final model. During the revision of the database, several new localities were added.

Second, the resulting dataset was manually quality-checked. Furthermore, a statistical outlier analysis was used to retrieve localities, which were evaluated again.

Finally, the HC localities were modelled using an interpolation technique that treated data points based on the confidence of the observations, where high-confidence points were allowed less variation from their elevation value, whereas points with low confidence were allowed more variation. To interpolate abrupt changes in HC-level, break-lines were included in the interpolation at the location of the drainage of the Baltic Ice Lake and the northern boundary of the Low Baltic Ice-stream. The resulting model provides a more detailed and accurate visualization of the HC of Sweden. In most regions, the elevation of the HC agrees with earlier observations, but in other places, such as the Kristianstad region, this new model yields considerably different results.

P31.2

Terrace and moraine chronologies provide complementary records of ice retreat in southeastern Tibet

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With global climate change, understanding the response of landscapes to shifting climate regimes is increasingly important. Glaciated mountain regions are especially sensitive, with glacier advance and retreat shaping the landscape and driving transport of glacially eroded sediments. Understanding the timing behind these processes is essential for reconstructing paleoenvironments and for anticipating future landscape change. On the eastern margin of the Tibetan Plateau, glaciated valleys and adjacent rift basins preserve both moraine complexes and extensive alluvial terraces, providing the opportunity to test the linkage between glacier fluctuations and terrace aggradation.

We present the first integrated study from the Shaluli Shan region of southeastern Tibet combining cosmogenic ¹⁰Be and ²⁶Al exposure age dating of moraines with infrared stimulated luminescence (IRSL) dating of alluvial terraces. We targeted two locations from the same catchment: Three moraine complexes and one associated alluvial terrace were sampled in the glacial Litang Valley, and two additional terrace levels were sampled downstream in the Kangga Basin. Concordant exposure ages of boulders on moraine crests show that the most extensive glaciation is mostly attributable to MIS 6, while global Last Glacial Maximum (gLGM) and Late Glacial extents were more restricted. IRSL dating of the associated glaciofluvial terrace confirms terrace aggradation following glacial retreat from the gLGM moraine and continuing until after the deposition of the Late Glacial moraine. In the Kangga Basin, the thickest and most extensive alluvial terrace was deposited after MIS 6, likely in multiple phases tied to MIS 6 deglaciation and MIS 5 stadial–interstadial transitions. A less extensive terrace level formed during MIS 2, correlating with contemporaneous glacier advances.

In the Litang Valley, the terrace ages reveal a close temporal relationship between glacier retreat and glaciofluvial aggradation: deposition began following glacier retreat from the distal moraine, continued during ice-margin stabilisation, and was only completed after glacier retreat from the proximal moraine. In contrast, terrace aggradation in the distal Kangga Basin post-dates glaciation maxima as inferred from moraine ages in the Maoyaba Basin. These results show that terrace aggradation correlates with glacier culmination and retreat, but time lags vary with geomorphic setting: distal locations record delayed responses, whereas proximal sites show more immediate coupling with ice-margin fluctuations. Our findings support terrace aggradation models previously proposed for the Tibetan Plateau. Ages of terrace deposits provide a robust complementary proxy to moraine chronologies. This combined approach refines our understanding of the coupling between glacial and fluvial processes and landforms in southeastern Tibet and contributes to linking paleoclimatic forcing with landscape evolution in high mountain environments.

P31.3

Late Quaternary palaeoceanography, ice dynamics and climate change across the Svalbard-North Greenland transect

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Large uncertainties in projections of global warming and associated sea-level rise largely stem from an insufficient understanding of the causes and effects of rapid climate shifts in the geological past. The dynamic environment of the late Quaternary including abrupt climate changes, rapidly accelerating ice-sheet melt and related meltwater fluxes is recorded in both the seafloor morphology and seabed sediments. These archives provide key insights into the processes driving past environmental change.

Here we present preliminary results from a study of palaeoenvironmental conditions and climate variability in two geographically and climatically different key areas: western Svalbard and North Greenland. Our focus is on rapid warming periods, such as the Bølling-Allerød in order to improve the understanding of the region's glacial and climate history.

The study is based on marine sediment cores analysed using a range of sedimentological and geophysical methods including lithological logging, magnetic susceptibility, shear strength, grain size analysis (IRD and sortable silt), foraminifera assemblage analysis and radiocarbon dating as well as stable oxygen and carbon isotope analyses ($\delta^{18}\text{O}$, $\delta^{13}\text{C}$).

We present preliminary results from two marine sediment records, one from Kongsfjordrenna Trough, western Svalbard and the other from the mouth of Independence Fjord, North Greenland. Both cores were retrieved at a grounding zone wedge where the glacier/ice sheet had a halt during deglaciation. Each core contains a basal diamict, suggesting a complete sedimentary succession since the last glaciation.

The geographical proximity of these sites, combined with their strong climatic and oceanographic gradients makes Svalbard and North Greenland ideally suited for studying the response of the Earth System to rapid climate changes in the recent past. Our findings have broad and important implications for accurate reconstructions of regional as well as pan-Arctic climate patterns necessary for validation of model-based projections of future climate and sea-level scenarios.

P31.4

New constraints for deglacial ice sheet dynamics in Saltfjorden, Nordland, Norway

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During the last glaciation, the Vestfjorden ice stream was amongst the largest outlet glaciers in the west-central sector of the Scandinavian Ice Sheet and was fed by tributary glaciers that occupied the modern fjords of Nordland, Norway. While the pattern of ice stream retreat during deglaciation is constrained by geomorphological mapping of high-resolution bathymetry, the timing of ice stream withdrawal is only approximated by few radiocarbon ages from distal marine sediment cores. Here, we summarize new terrestrial cosmogenic nuclide (TCN) exposure ages, radiocarbons ages, multibeam and subbottom echosounder data, and marine sediment cores that place constraints on the extent and thickness of an outlet glacier in Saltfjorden, a former tributary to the Vestfjorden ice stream.

New multibeam echosounder and subbottom profiler surveys outline a prominent grounding zone wedge at ca. 220 m depth near the fjord mouth, immediately south of Bodø. Sediment cores from the grounding zone wedge enable a depositional model for the stratigraphy and yielded multiple minimum-limiting radiocarbon ages for the emplacement of the ice-contact deposit. The results suggest that this ice-marginal position was abandoned by the onset of the Younger Dryas, ca. 13 cal ka BP. New TCN exposure ages, collected from varying elevations on two summits that formerly flanked the margins of the glacier in Saltfjorden, approximate rates of glacier thinning during the late-glacial period. TCN ages from a summit immediately to the south of the grounding zone wedge indicate that the ice sheet thinned from 420 to 225 m asl between ~16.2 ka and 14.4 ka. Additional TCN exposure ages from a summit ca. 25 km east of the fjord mouth (i.e. up-ice) indicate that the ice sheet thinned from 710 to 475 m asl between ~12.9 and ~12.3 ka. These results are consistent with the new minimum-limiting radiocarbon ages from the grounding zone wedge and, together, indicate that the ice margin was situated within the fjord by ~13 ka. A sequence of grounding-line moraines, immediately to the southeast of the grounding zone wedge, possibly delineates the position of the Saltfjorden outlet glacier during the Younger Dryas. However, if the TCN exposure ages are correct, then this marine glacier margin was concomitant with increased rates of ice surface lowering. These dynamics possibly contrast with adjacent cirque glaciers and other marine-terminating outlet glaciers that readvanced to deposit end moraines at this time, suggesting that possible feedbacks related to relative sea-level, bathymetry, and/or shifting centres of ice dispersal were dominant in regulating ice marginal oscillations in Saltfjorden during the late-glacial.

Reconstructions of past ice sheet dynamics in the study area, combined with new relative sea-level data, potentially place limits on the behaviour of the larger Vestfjorden ice stream and contribute to future GIA and ice-sheet modelling.

O33.1 (Keynote)

Mine Waste Monitoring with the M4Mining hyperspectral imaging system

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The EU-funded M4Mining consortium (Multi-scale, Multi-sensor Mapping and Dynamic Monitoring for Sustainable Extraction and Safe Closure in Mining Environments) has developed a drone-borne hyperspectral imaging solution integrated with LiDAR. This system delivers mineral classification maps to decision-makers in real time. LiDAR data is stored in a triangular mesh format with the hyperspectral data projected on to it, which preserves spatial connectivity while reducing storage size compared to rasterised formats. The system employs the HySpex Mjolnir VS620 hyperspectral imaging system, which provides centimetre-scale resolution mapping. It captures both visible–near infrared (VNIR; 400–1000 nm) and shortwave infrared (SWIR; 1000–2500 nm) data using dual co-aligned pushbroom sensors mounted on a gimbal that enables both nadir and oblique imaging up to a 40° roll.

This solution was tested at multiple mining sites to demonstrate how hyperspectral imaging can support ore deposit detection, environmental impact monitoring, and risk management for tailings and waste sites. Many ores, such as copper in chalcopyrite, do not have spectral diagnostic features; therefore, associated minerals are used as proxies for detection. Alteration minerals are valuable indicators; not only as proxies for the ore but also for revealing the environmental vulnerability that the deposit poses to vegetation and water sources.

One demonstration took place at the abandoned Memi sulphur mine in the Republic of Cyprus, a volcanogenic massive sulphide (VMS) deposit with waste heaps rich in pyrite. The site, abandoned in 1990, now serves as a testbed for mapping Acid Mine Drainage (AMD) extents using hyperspectral data. Secondary iron minerals, such as the spectrally active hematite, goethite, and jarosite, are pH-sensitive and therefore serve as proxies for AMD severity. Our spectral classification confirms jarosite and goethite as the dominant surface minerals at the Memi mine tailings, highlighting jarosite-rich zones as areas of highly acidic conditions. Thus, hyperspectral imaging serves an effective monitoring tool.

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033.2

Acid Mine Drainage Assessment Using Multispectral Drone Imagery and Machine Learning: A Case Study from Outokumpu, Finland

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Acid Mine Drainage (AMD) is a critical environmental problem that arises from the oxidation of sulfide-rich rocks in abandoned mines or mining-disturbed areas. This process results in the release of acidic water with high concentrations of dissolved metals, often leading to a significant reduction in the pH of nearby water bodies. Traditional monitoring methods such as field sampling and laboratory analysis are typically resource-intensive and limited in spatial and temporal coverage. In contrast, remote sensing technologies offer efficient and cost-effective solutions for AMD monitoring, overcoming many of the limitations of conventional approaches.

To support AMD assessment, we acquired radiometrically calibrated multispectral drone imagery using a WingtraOne fixed-wing UAV equipped with an integrated MicaSense Altum sensor over the Outokumpu mining area in Finland, a region affected by mine waste and acidic drainage. Data collection focused on four lakes with different characteristics: Sysmäjärvi, Outolampi, Alimmainen Hautalampi, and Kuusjärvi. The first three lakes have been impacted by historical mining activities, whereas Kuusjärvi served as a reference site due to the absence of known contamination. In addition to drone imagery, 10 water samples were collected from these lakes during 20–21 May 2024 to capture a range of acidification levels.

We employed Random Forest (RF) for pixel-wise AMD classification using drone imagery. RF is a widely used machine learning method in ecological monitoring, water quality assessment, and land cover classification. To address the challenge of limited labeled data, synthetic samples were generated using the Gaussian Copula Synthesizer (GCS). GCS preserves multivariate dependencies among features to provide high-fidelity data augmentation that reduces overfitting and improves model generalization.

We evaluated model performance and generated AMD maps for each lake, showing the predicted pH values for every pixel in the imagery. Our experimental results demonstrate that the inclusion of synthetic data effectively mitigated the limitations posed by the very small labeled dataset (only 10 samples) in a supervised learning such as RF, leading to improved model performance and generalization. Overall, our AMD mapping approach provides a scalable and cost-effective solution for monitoring and managing mining-impacted water bodies, thereby supporting informed decision-making in environmental protection and remediation efforts.

Acknowledgments

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033.3

Mineral mapping for tailings management facility rehabilitation with hyperspectral UAV data – a case study from Chalkidiki, Greece

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Historic tailings can contain valuable minerals that were not extracted during initial processing. They may also pose environmental risks because of sulphur and heavy metal containing minerals. Whilst drilling and laboratory analysis are required for accurate resource estimation in the sediments of the tailings management facilities (TMF) and potential soil contamination; hyperspectral imaging may guide the remediation process as it enables mineral mapping of the sediments exposed on the surface. The goal of the research in MultiMiner project was to determine if the uncontaminated substrate soils could be separated from the TMF sediments based on UAV-carried hyperspectral imaging (HSI) data to guide a remediation process in Chalkidiki, Greece.

The study site is the former Olympias TMF which was reclaimed by Hellas Gold in 2016-2025 (Lopez-Pacheco 2025). In September 2024, the site was visited to acquire HSI data with a UAV-mounted HySpex Mjölnir VS620 (Norsk Elektro Optikk). Also, twelve surface sediment samples were collected, spectra were measured with field spectrometer, and these samples were later characterized for their quantitative mineralogy by XRD. Hyperspectral data were analysed by mapping the wavelength position of the mineral diagnostic absorption features and mineral mapping with Spectral Angle Mapper (SAM).

Based on the XRD results, the samples could be classified into three sample types. The samples of the original substrate sediments and the cleaned site were dominated by quartz, feldspars and clay minerals, goethite. The tailings material composed the other sample type which also contains 20-30 wt.% of carbonate minerals calcite, dolomite and rhodochrosite, and significant amount of sulphur phases such as gypsum and pyrite (~20 wt.% combined). The third sample type is a mixture of the two previous ones which covered the access roads and showed the combined features of the original soil and tailings.

The diagnostic absorption features of carbonates, gypsum and clay minerals were central for distinguishing tailings and mixed sediments from the background. Tailings and mixed sediments were successfully separated from uncontaminated soils using SAM classification. Reference spectra for classification were taken from the USGS spectral library, including the carbonates, gypsum and silicates (muscovite, illite, kaolinite, vermiculite, biotite), and goethite. The classification method successfully separated tailings from the substrate soils, even though the absorption features were weak because of mineral mixtures, intense weathering, and alternating lighting conditions during data collection. In this particular case study, the contaminated tailings and uncontaminated background could be distinguished using UAV HSI data, offering a non-invasive tool to support effective environmental monitoring and rehabilitation of TMFs.

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O33.4

Ground Moisture Monitoring Using Time-Series Sentinel-1 C-band SAR Images and Auxiliary Datasets

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Soil moisture monitoring in mine sites is crucial as mining activities alter subsurface hydrology, disturb natural water retention, and affect recovery of rehabilitated vegetation (Zhang et al. 2022). Large-scale soil moisture retrieval is made possible using earth observation and remote sensing technologies, which provide efficient ways to track soil moisture (Antropov et al. 2024; Bauer-Marschallinger et al. 2018). Despite current methods, which allow coarse soil moisture prediction over non-vegetated areas at 1 ha and 1 km² mapping units, we aim to develop a SAR-based mapping approach for precise moisture retrievals at much finer mapping units by incorporating knowledge about studied sediments and auxiliary datasets.

This research developed a machine learning-based approach using time series Sentinel-1 data and auxiliary data, such as Sentinel-2, digital surface model (DEM), metrological data, and soil texture type information over a limestone quarry in Lappeenranta, Finland. The in-situ reference soil moisture measurements were collected from various sediment types using IoT-enabled capacitance sensors. The explanatory variables were organized into distinct feature sets to evaluate the individual contribution of Sentinel-1 data features and their incremental value when combined sequentially with auxiliary datasets.

According to the results, ensemble-based algorithms, particularly Light Gradient-Boosting Machine (LightGBM), when applied to the full feature set of time-series Sentinel-1 and auxiliary data, can enhance the accuracy of surface soil moisture estimation. The algorithm trained using only Sentinel-1 data achieved an RMSE of 7.53 %, which was further reduced to 5.31 % when auxiliary data were incorporated. The resulting soil moisture maps can support early detection of seepage or unstable zones, which will directly help make mine management safer and more efficient.

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O33.5

Drone-based bathymetric measurements in the assessment of the Impounded Riverbed of Rautuvaara

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In mining operations, the modification of streams and rivers is sometimes necessary to accommodate future activities. To preserve the natural state of these water bodies, it is essential to conduct thorough environmental assessments before, during, and after such modifications. One of the key challenges has been the mapping of riverbed morphology and underwater terrain, which is traditionally labor-intensive and slow. Riverbed profiles influence flow dynamics and, consequently, the dispersion of industrial effluents in receiving water bodies. They are also critical for planning ecological restoration, such as spawning grounds and habitats for juvenile migratory fish.

The UOMARI project develops and tests drone-based measurement and imaging solutions aimed at reducing environmental impacts and risks associated with industrial activities, particularly in the mining sector. In this study, the dammed riverbed of the Niesajoki River at the former Rautuvaara mine was investigated using a dual-wavelength laser scanner and ground-penetrating radar (GPR) adapted for drone deployment. The laser scanner operates at wavelengths of 510 nm and 1030 nm, where the shorter wavelength penetrates water and the longer reflects off the water surface. The GPR system, operating at 100 MHz, utilized real-time sampling and hardware stacking.

For reference measurements, an autonomous unmanned surface vehicle equipped with single-beam and side-scan sonar was used to generate a depth map of the channel. These measurements revealed the channel's morphology clearly, with a maximum observed depth of 5 meters. Drone ground-based radar produced comparable depth data, although with lower accuracy. The dual-wavelength laser scanner did not detect features underwater, as water impurities and humus prevented the laser beam from penetrating the water.

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O33.6

Application of vegetation growth analyses from optical remote sensing satellite data for phosphate (+REE) exploration in the Norrbotten area, Sweden – first results and conclusions

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Applications of optical remote sensing data (Earth Observation data) for mineral exploration are in general limited to areas free of vegetation due to lack of penetration into the subsurface. An exception might be the search for areas with elevated concentrations of phosphate in the soil based on estimated and classified vegetation growth. The Per Geijer Ore bodies in the Kiruna Mining district are known to host elevated concentrations of phosphate and Rare Earth Elements, and an exploration model is therefore proposed in which a search is made for areas with local high gravity and magnetic that coincides that are associated with high vegetation growth.

Vegetation classification based on remote sensing data is used extensively in forestry and farming but has so far not been used for mineral exploration as investigated here. We present the very first results from an ongoing Horizon Europe project referred as MinEYE in which the Norrbotten study is one out of three case study areas involving Earth Observation techniques for mine life cycle monitoring using ML-based data fusion approaches.

Many different parameters influence vegetation growth, such as soil composition in general, local climate conditions, hydrological parameters, cultural activities, etc. Differences between year are also present due to climate variations. Thus, analyses of the remote sensing

Many different parameters influence vegetation growth, such as soil composition in general, local climate conditions, hydrological parameters, cultural activities, etc. Differences between years are also present due to climate variations. Thus, interpretations of classifications results are not straightforward, and furthermore made complicated due to the huge amount of data. Our approach is therefore based on an initial analysis from gravimetric and magnetic data which allow screening of areas for detailed vegetation analysis.

033.7

Mineralogical investigation on basalts from Disko, Greenland, using SEM and hyperspectral image analysis

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Basaltic lava flows from Disko, West Greenland are potential target to sequester CO₂ that else would be emitted into the atmosphere. In this study, we integrate hyperspectral (HS) imaging with scanning electron microscopy (SEM) to characterize the mineralogy of five drill core boxes of variably altered basalts as well as 8 hand specimen of picritic hyaloclastic and other Mg-rich basalts. Hyperspectral data were acquired using HySpex sensors in the SWIR (640–2500 nm) and VNIR (400–1800 nm) ranges and analyzed using Minimum Noise Fraction (MNF) to guide targeted SEM analysis. Both qualitative and quantitative results were achieved from the HS dataset through the use of Iterative Spectral Mixture Analysis (ISMA) and the Maximum Fraction methods.

HS proved effective in distinguishing between phyllosilicates (including clays), zeolites, and primary basaltic minerals with overlapping chemistry, owing to its sensitivity to structural water content. Automated mineralogical quantification (AQM) via SEM allowed chemical separation of minerals with similar spectral signatures, thus complementing the HS results. The combined approach provided new insights into (i) the abundance of olivine, anorthite, and Mg-rich pyroxene relevant for CO₂ mineral sequestration potential, (ii) the distribution of alteration minerals, and (iii) the occurrence of pore-filling phases influencing reservoir properties.

Together, HS and SEM deliver a multiscale framework for linking outcrop, reservoir, and microscopic observations. These results enhance our understanding of the dynamics of lava flows and the post-emplacement geological history of Disko basalts, while demonstrating the value of integrated methods for assessing mineral reactivity and reservoir quality in volcanic systems.

033.8

The importance of data feature extraction from airborne geophysical and remote sensing data prior to machine learning and geostatistical clustering and structural interpretations

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Although significant advances have been made during the last decades on the use of machine learning and geostatistical algorithms for clustering/classification of spatially distributed multi-variate data, a significant task prior to application of these tools need to be devoted to proper data feature definition and extraction from the sourced data. Data features such as lineaments are furthermore significant input to structural interpretations in areas of low degree of rock exposures. This presentation provides examples to illustrate the statements above. Additionally, a new method for identifying remanent magnetization in airborne/drone magnetic data is presented. This method also provides estimates of magnetic declination which in certain cases might be of importance for the use of strike measurements based on compass readings.

Examples are presented from different geological settings. Data from the Northern Norrbotten ore province are analyzed with special focus on remanent magnetization of Iron Oxide Apatite ore bodies. Potential field data from the Swedish “Nickel Line” south of the Skellefte district are discussed. A case study involving IOCG and VMS mineralization from the Iberian Pyrite Belt are also showcased to illustrate the applicability of the proposed methodologies.

033.9

Exploring the potential of very high-resolution multispectral satellite imagery for bedrock lithology mapping applications in a Nordic context

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Over the past decade, very high-resolution (VHR) multispectral satellite imagery has established itself as a cost-efficient source of optical remotely sensed data for mapping applications in Earth sciences. Imagery collected by commercial Earth observation satellites, such as WorldView-2/-3 and the PlanetScope constellation, spans the visible to near-infrared (VNIR) radiometric spectrum, extending in some cases into the short-wave infrared (SWIR) region, at a spatial resolution as high as 0.3 m. Multispectral VHR imagery has been successfully leveraged to map land cover types, natural and anthropogenic disasters, shallow-water environments, to monitor civil infrastructure and mining operations, and to guide mineral exploration.

Applications of VHR satellite imagery in bedrock lithology mapping are well known from the literature (e.g., Hubbard et al. 2023; Mars 2018). Existing reports tend, however, to focus on arid or anthropogenic environments, while in a Nordic context, potential applications face a set of challenges specific to boreal post-glacial landscapes. These challenges consist primarily in the need to distinguish (1) between exposed geological surfaces and vegetated surfaces and, within the extent of the former, (2) between bedrock and Quaternary sediments.

This study addresses the two challenges by first applying a neural network-enabled computer vision technique to a band stack of color infrared aerial imagery and LiDAR data to detect bedrock outcrops in the former mining district of Feragsfjella in eastern Norway. The outcrop mask was then applied to the 16-band

WorldView-3 VNIR-SWIR imagery (1.2 m to 3.6 m resolution). Using a combination of physics-based spectral hourglass and spectral angle mapper methods, the resulting outcrop pixels were classified into broad lithological classes (serpentine, augen gneiss, phyllite, arkose, etc.), by leveraging the existing field bedrock observations database maintained by the Geological Survey of Norway.

By demonstrating the potential of VHR satellite imagery for lithology mapping in vegetated boreal regions, this study invites further exploration into the applications of high-resolution hyperspectral satellite imagery, potentially super-resolved through fusion with VHR imagery. Considering the extensive amount of VHR satellite imagery collected by satellite operators, the proposed workflow may facilitate early stages of mineral exploration and prospectivity mapping.

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P33.1

Bed-form scale changes in a sub-arctic meandering river: geomorphological evolution under different hydrodynamic conditions

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Understanding changes in meandering rivers is crucial for assessing how rivers respond to changing hydrological conditions, especially in high-latitude environments. The study examines geomorphic changes in a sub-arctic sand-bed meandering river, in northern Finland over a nine-year period (2015–2024). Using high-resolution LiDAR derived digital terrain models (DTMs) and orthophoto mosaics, we examine adjustments of point bars, channel thalwegs, and floodplains in response to varying hydrodynamic conditions, incorporating flood magnitude data.

We quantify these with the help of GIS based spatial analysis for channel migration rates, elevation differences, and sediment redistribution. Orthophotos are further analyzed to quantify vegetated versus unvegetated areas, enabling us to investigate the role of riparian vegetation on sediment stability and flood resistance. Integration of DTMs with seasonal orthophoto data will enable us to visualize maximum inundation extents and changes in sediment transport patterns.

Preliminary findings indicate significant morphological changes at point bars, where seasonal flooding has led to the redistribution of sediment downstream. Areas with well-established vegetation appear to experience less erosion, while bare or sparsely vegetated zones show greater susceptibility to sediment displacement.

By using high-resolution temporal data, we are able to track even slight changes that can still be statistically significant in the river system. This information adds to the knowledge of meandering river dynamics and helps develop management policies within river systems under ever-changing hydrological regimes.

034.1

Integrating Geochemical and Remotely Sensed Data for Regional-Scale Predictive Mapping: An NGU Perspective

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The implementation of artificial intelligence (AI) in predictive mapping has expanded rapidly across fields such as mineral exploration, environmental geochemistry, and ecological studies. High-resolution, remotely sensed datasets—including topographic, spectral (satellite), radiometric, and magnetic surveys (typically 10–250 m resolution)—are widely used as covariates in both classical and deep-learning models. By contrast, geochemical datasets present greater challenges for integration. In Norway, their sampling resolution is typically 1–2 orders of magnitude coarser than remotely sensed data (e.g., 1 sample per 1–4 km² local surveys) and can be even sparser at regional scales (up to 1 per 36 km²). Additional complications arise from batch effects linked to laboratory analyses, inconsistencies in sampling protocols (particularly in legacy datasets), and variable sampling densities where regional and local surveys overlap. These factors make direct use of geochemistry as model input particularly challenging for county- to national-scale studies.

The Nordland and Trøndelag counties of Norway host multiple stream sediment and mineral soil geochemical surveys with heterogeneous sampling densities (ranging from ~1 sample per 2 km² to 1 per 36 km²). In this contribution, we present a workflow to harmonize these datasets and generate valid raster maps for integration into AI-based predictive mapping. Stream sediment and soil data were treated independently. First, censored values were imputed using an expectation–maximization approach in log space. Second, data levelling was applied through linear regression–based correction factors and/or Z-score normalization, depending on shared standards or re-analysed samples. Once harmonized, the datasets underwent dimensionality reduction using both linear (PCA) and non-linear (UMAP) methods to efficiently capture variability and reduce redundancy.

Principal component and UMAP vectors were interpolated using Empirical Bayesian Kriging (EBK), carried out independently for each survey. The associated standard errors (SE) were used to merge local and regional datasets, giving local predictions more weight where available to reflect higher sampling density. Inverse variance weighting ensured that estimates with lower uncertainty contributed more strongly, while regional predictions provided coverage where local data were absent. This produced merged rasters balancing the detail of local surveys with the continuity of regional datasets, providing consistent, spatially comprehensive predictors for subsequent modelling.

Overall, this study presents a practical strategy for transforming heterogeneous geochemical surveys into harmonized, uncertainty-weighted raster covariates. The workflow bridges sparse geochemical data and dense remotely sensed information, enhancing the robustness of AI-driven predictive mapping at regional to national scales.

O34.2

Scientific machine learning for geophysical modelling, inversion, and uncertainty quantification

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With recent advancements in machine learning (ML) and artificial intelligence (AI), a central question arises: how can established workflows of geophysical modelling and inversion benefit from these methods without sacrificing robustness and physical consistency? Scientific machine learning offers a pathway by respecting physical principles during the learning process, combining the strengths of physics-based formulations with the adaptability of neural networks. This integration enables flexible representations of the Earth while maintaining the reliability of traditional forward and inverse approaches.

In this contribution two complementary directions are discussed. The first is how neural networks can be trained to *solve geophysical forward problems* and subsequently used as fast surrogates to accelerate inversion and uncertainty analysis. This approach is demonstrated with magnetotelluric modelling and probabilistic inversion, where deep operator networks emulate magnetotelluric responses and make large-scale probabilistic exploration feasible. The second direction is how *geophysical inverse problems themselves can be solved by neural networks*, where the subsurface is represented as a continuous neural function directly constrained by physics. This is demonstrated through three-dimensional gravity inversion, where implicit neural fields capture both gradual variations and sharp contrasts without the need for explicit regularisation. Together, these advances point toward a new generation of geophysical workflows, opening space for geoscientists to explore a broader range of geological possibilities. While challenges remain in generalisation, data quality, and the incorporation of geological priors, scientific machine learning offers a promising framework for building Earth models that are both physically faithful and computationally efficient.

O34.3

Artificial Intelligence in Mineral Exploration (AIMEX): Advancing Sustainable Mineral Exploration Targeting through Scientific Computing and Machine Learning

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The **AIMEX** project (**Artificial Intelligence in Mineral Exploration**) is a multidisciplinary initiative led by the Geological Survey of Finland (GTK), in collaboration with the University of Turku, the Finnish Environment Institute, and several industry partners. Funded by Business Finland, AIMEX aims to modernise mineral exploration by integrating scientific computing, spatial data analysis, machine learning, and sustainability-driven decision-making into a unified framework for mineral prospectivity mapping.

AIMEX responds to the growing need for efficient, data-driven exploration methods in both greenfield and brownfield settings. Traditional mineral exploration workflows are often time-consuming, resource intensive, and constrained by fragmented datasets and manual interpretation. AIMEX introduces a suite of user-friendly software tools that apply machine learning algorithms to automate pattern recognition, integrate multi-source geoscientific data, and generate mineral prospectivity maps at real-world exploration test sites in collaboration with industry partners.

The project employs a range of machine learning techniques to process large volumes of spatial data, including geological, geochemical, and geophysical datasets. In addition, AIMEX develops tools that enhance exploration workflows using hyperspectral and drill core imagery. Advanced image processing methods are applied to improve drill core data quality and support automated classification.

A key innovation of AIMEX is its holistic approach to mineral exploration. The decision-making system under development incorporates not only geological and economic factors but also environmental, social, and governance (ESG) constraints— such as nature conservation areas, current other land use, and future land use planning. This ensures that exploration strategies align with responsible resource development and EU policy goals.

Selected capabilities from machine learning algorithms and ESG data are embedded in intelligent applications designed to support geoscientists in exploration targeting and feasibility assessment. By combining cutting-edge machine learning techniques with robust geoscientific knowledge, AIMEX demonstrates how scientific computing can accelerate discovery, reduce environmental impact, and support informed decision-making in the search for critical raw materials.

The outcomes of AIMEX have direct application potential in the global mining industry and contribute to the digital and green transition of Europe's raw materials sector.

O34.4

OttoVision: Toward a national lineament map with machine learning

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Digitizing bedrock lineaments is a labour-intensive process prone to interpreter bias, especially when integrating multiple data sources like orthophotos and DTMs (Scheiber et al. 2015). While automatic extraction is the ideal solution, early algorithms struggled with complex landscapes, resulting in under-detection, poor connectivity, and high false-positive rates. Moreover, their geological utility was limited by the inability to distinguish between feature types, such as bedrock lineaments and alluvial incisions.

The Geological Survey of Norway (NGU) is tasked with creating national fault and fracture maps at multiple scales. While topographic lineaments are not necessarily faults or fractures, a low-bias, automatically generated lineament map provides an essential template for subsequent geological mapping. In the ongoing “Fracture and lineament database” (BLID) project, we have developed an in-house machine learning algorithm (OttoVision) that addresses the aforementioned limitations of earlier attempts. Our convolutional U-Net model, trained on expert-annotated tiles from diverse Norwegian landscapes using multiple DTM derivatives as input, reproduces geologically meaningful lineament patterns with high fidelity.

Applied at a national scale, this approach generates a reproducible, low-bias lineament map directly from topographic data. This product provides a consistent foundation for regional to national studies of bedrock structure, resource potential, and geohazard assessment.

This presentation will showcase our current national lineament map (10m resolution) and discuss its strengths and remaining challenges.

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P34.1

Building uncertainty-aware subsurface models with 3D magnetotelluric inversion

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Magnetotellurics (MT) images electrical resistivity, a property influenced by fluids, alteration, graphite, and partial melt. Because many different subsurface configurations can explain the MT responses observed in the field, the preferred subsurface conductivity model estimated through inversion is often ambiguous. A central challenge is that true stochastic model exploration, in 3D, while conceptually the best way to expose such ambiguity, is too computationally demanding to be used as the state-of-the-art. Consequently, most studies report a single deterministic model, which obscures the range of alternative geological structures that are equally consistent with the data.

In this work we propose a practical approach to stochastic model exploration in 3D MT inversion. Drawing inspiration from annealing methods, we adopt a Very-Fast Simulated Annealing framework, with sparse parameterization that make the search feasible for large-scale problems (Sen & Stoffa 2013). Our inversion algorithm is built around the widely used ModEM forward solver (Kelbert et. al. 2014), ensuring compatibility with existing workflows. Instead of producing one definitive model, the workflow can generate a set of plausible models that more or less explain the data equally well. From this ensemble one can compute statistical summaries: a mean model that captures the most consistent structures and quantitative measures of variability that highlight where geometry, depth, or connectivity remain uncertain. This representation enables geologists to make interpretations while being explicitly aware of the uncertainty inherent in the inversion. We demonstrate that the approach works at regional scale using a large-area subset of USArray MT data from Cascadia (Patro & Egbert 2008). This dataset has been extensively studied and previously modelled with deterministic 3D inversion, which allows us to benchmark our results.

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P34.2

3D EM Modeling and Inversion: A Comparative Study of Numerical Solver Efficiency and Practical Application to Field Data

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We are developing an efficient and robust 3D EM inversion code for interpreting diverse responses simultaneously, ultimately producing a unified multiscale resistivity model. The code will be valuable for both commercial and educational applications. This abstract details the implementation framework and its current development status, with a focus on solver performance comparison for modeling and inversion applications.

For CSEM and MT forward modeling, we utilize curl-conforming Nédélec elements to solve Maxwell's equations in the frequency domain. Specifically, CSEM employs a total electric field formulation, while MT uses a secondary field approach. To accommodate large models with sufficient resolution, we utilize separate octree grids for meshing in the forward and inverse domains. Written in C++, the code allows for flexible adaptation to various source and response types, e.g., plane waves, dipoles, line/loop sources, as well as MT impedance and tipper vectors; electric and magnetic field responses are already supported.

The inverse problem is solved by minimizing misfit using a Gauss-Newton scheme with explicit Jacobian computation. The optimal regularization parameter is determined iteratively via the Occam approach. We've implemented three regularization methods: Tikhonov, flatness, and Raviart-Thomas finite element smoothness. The unified inversion mesh enables the joint inversion of diverse responses. The implementation was built on the deal.II library, which provides interface wrappers for numerically computationally intensive tasks, such as system equation solving (MUMPS) and inversion model update (PETSC Conjugate Gradient solver). Our code is fully parallelized with MPI for both forward and inverse modeling.

In this study, we evaluate the computational performance of two direct solvers, MUMPS and WSMP, which are used to solve the linear system of the forward problem. The results of applying our developments to the field data will be demonstrated on-site.

035.1

Temperature and compositional variation of the geothermal fluid in the Reykjanes geothermal system, Iceland

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The Reykjanes geothermal field is located where the Mid-Atlantic Ridge meets Iceland. It is a seawater-dominated system that has been suggested to be an on-land equivalent of basalt-hosted seafloor hydrothermal systems forming black smokers and massive sulfide deposits. A dataset of fluid composition from 3.1 ± 0.1 , ~ 3.6 , and ~ 4.3 km borehole depth was created by analyzing secondary fluid inclusion assemblages (FIAs) by microthermometry, Raman spectrometry and LA-ICP-MS in recovered drill cores from the RN-15/IDDP-2 well. These FIAs were identified to represent current fluid composition at depth. The dataset includes 22, 34, and 31 vapor- and liquid-rich/brine FI signals from 10, 8 and 11 secondary FIAs, respectively. Added to the dataset were fluid composition data from 4.6 km borehole depth (Bali et al. 2020), shallower in-situ (~ 1500 m depth) and well head fluid data (Harðardóttir et al. 2009). At all depths, phase separation is recorded within all studied secondary FIAs, halite saturation is observed at 4.3 km depth and two different fluid generations were identified at 3.6 km depth. Recorded FIA trapping temperatures are ~ 300 °C at 3.1 km depth, 300 & 340 °C and 3.6 km depth, ~ 430 °C at 4.3 km depth and to ~ 600 °C at 4.6 km depth. The molar ratio in between the major cations at 4.6 km depth, Fe, Na and K, is $\sim 1:1:1$ and all fluid inclusions fall in a well-defined, narrow compositional range. Inclusions from 4.3 km depth show much larger variations in Fe-Na-K ratios, and Ca and Na concentration increase significantly while K decreases. Large variations are also found for concentrations of minor and trace elements at this depth, this can be explained by halite saturation and likely other mineral precipitation (i.e. CuFeS). Fluid at this depth contains high amounts of trace metals e.g. median concentrations of Cu, Zn and Ag of 638, 2864 and 1.4 ppm, which is up 10^9 times enriched compared to seawater. At 3.6 km depth, we observe an even greater elemental variability in between the two generations of trapped fluids, which likely mix at this depth, one representing the upwelling deeper fluid and the other one being an inflow from a shallower feed zone. They are mainly distinguishable by their different Fe contents, however some elements like Zn and Pb are as enriched as in deeper fluids, in both fluid generations. Precious metals concentrations in fluids at 3.6 km depth and deeper are higher than in black smoker fluids reaching almost concentrations like porphyry ore deposit-forming fluids. Fluid inclusions from ~ 3.1 km depth have similar Fe-Na-K molar ratios as seawater and the geothermal fluid sampled at the well head and at ~ 1.5 km downhole depth and are comparable to submarine black smoker vent fluids.

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O35.2 (Keynote)

Salt melt halogen signatures link Kiruna-type Fe–P–REE ores to magma–sediment interaction

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Kiruna-type magnetite–apatite (MtAp) deposits host massive concentrations of iron and are often enriched in phosphorus and rare earth elements, yet the nature and source of the fluids forming these systems remain debated. Central to this debate are Fe-rich chloride–carbonate–sulfate salt melt inclusions, ubiquitous in MtAp deposits and likely relevant for Fe–P–REE transport (Xu et al. 2024). These have been variously interpreted as magmatic–hydrothermal fluids, residual melts formed via immiscibility triggered by evaporite assimilation, or anatectic melts from partial melting of evaporite-bearing rocks.

We present LA-ICP-MS triple-halogen (Cl–Br–I) data from MtAp deposits at El Laco, Laco-Salar (Chile), and Hormuz Island (Iran), and compare them with Fe–K–Na salt melt inclusions from the Biely Vrch and Slatinské Lazy porphyry–Au deposits (Slovakia). These arc-type magmatic–hydrothermal systems record exsolution of hypersaline brine that lost H₂O to vapor and precipitated NaCl during ascent, generating K–Fe-rich salt melt (Koděra et al. 2014). This process mirrors certain genetic models for MtAp formation and represents a suitable analog for testing competing hypotheses.

MtAp salt melts have very low Br/Cl and I/Cl ratios similar to evaporite rocks, whereas porphyry–Au melts have higher ratios typical of arc magmatic–hydrothermal systems. Fluid–fluid mixing, magmatic fractionation, or fluid–rock interaction cannot produce the halogen signatures of the MtAp systems within a magmatic–hydrothermal framework. Instead, the data point to an evaporitic source of chloride and require magma–sediment interaction as a dominant formation mechanism. The triple-halogen approach provides a powerful and transferable tracer of magma–sediment interaction, with clear potential for application to other MtAp occurrences, other mineral systems in which such interactions are suspected (e.g., skarns, layered intrusion–hosted Ni–Cu–PGE) (Xue et al. 2023), and possibly even to large-scale magmatic events where melt–evaporite interaction has been linked to climate perturbations (Sibik et al. 2021).

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035.3

Initial Results and Techniques using Fluid and Melt Inclusions to Constrain the Role of Depth-Controlled Fluid-Mediated Metal Distribution in Alkaline-Carbonatite Magmatic Systems

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Intrusive alkaline rock and carbonatite complexes, of which many exist in the Nordic region, represent major potential sources of critical metals like Nb, Ta, REEs, Zr, Hf, or Ti, and could play a key role in the Critical Raw Materials Act (Goodenough et al. 2018). Despite the economic importance of ultramafic alkaline and carbonatite complexes, their formation is contested. On one side, the vertical and lateral zonation in both lithologies and metal inventories often observed in these complexes has been linked to magmatic differentiation processes at varying depths (Frolov 1971; Woolley & Kjarsgaard 2008). Conversely, it has also been suggested that they are metasomatic, with zonation being caused by ascending low-viscosity carbonatite melts being progressively consumed during reaction with silicic country rocks (Vasyukova & Williams-Jones 2022).

No LA-ICP-MS studies have yet quantified metal contents in fluid and melt inclusions from alkaline silicate and carbonatite systems, and halogen budgets remain unconstrained. The data obtained from inclusions will provide the basis for evaluating metal transport in such systems and the role of externally derived fluids in metal redistribution, which is critical for understanding both lithological and metal zonation (Walter et al. 2021).

Representative samples were selected from the Kola Alkaline Province, including Sokli, Finland; Ol Doinyo Lengai, Tanzania; and Kalkfeld, Namibia. Analysis was conducted on fluid and melt inclusions in a wide variety of rock types from each deposit using EPMA, Raman, and LA-ICP-MS. Additionally, our workflow introduces the use of ion beam milling to expose melt inclusions. This technique is much more efficient than using focused ion beam. We report the first results on element concentration data from fluid and melt inclusions of alkaline ultramafic and carbonatite complexes.

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O35.4

Mineral chemical heterogeneity in the episyenites of the Proterozoic Suomenniemi rapakivi complex, southeastern Finland: Insights into high-temperature metasomatic processes

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Alkali-rich fluids percolating through the upper mantle and crust can cause significant geochemical and mineralogical changes to the host lithological units. One such metasomatic process called episyenitization, occurs in granitoids, and is characterized by the leaching of quartz and formation of sodic amphibole and/or pyroxene as well as hydrothermally recrystallized alkali-feldspar. The reactions between the enriched fluids and the host rock have been linked to enrichment of varying commodities such as rare earth elements (REE), U and P (Barton & Johnson 1996). Episyenite systems are rather underexplored owing to the complexity of metasomatic recrystallization, controlled by highly varying fluid composition, temperature, and O fugacity.

The Suomenniemi rapakivi granite complex in southeastern Finland hosts quartz-poor, Na-augite and aegirine-rich episyenite dykes, interpreted to be the result of pervasive recrystallization caused by alkali-rich fluids (Suikkanen & Rämö 2017, 2019). This process has dissolved quartz in the granite protolith and precipitated metasomatic alkali-feldspars, sodic amphibole, titanite, and carbonate minerals, as well as sodic pyroxene after igneous amphibole. There are notable geochemical and mineralogical differences between Suomenniemi episyenite bodies, implying varying interaction between the host rock and infiltrating hydrothermal fluids.

In this project we use major and trace element geochemical data from 12 different episyenite bodies in Suomenniemi, using the mafic rock forming minerals, namely amphibole and clinopyroxene. Electron microprobe data (EPMA) on them highlights the considerable heterogeneity (e.g. Na, Si, Fe & Ti content) in the episyenites of the Suomenniemi complex, caused by varying fluid composition, temperature, or even different fluid generations. Trace element mineral chemical data acquired via Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) demonstrating mobility in elements traditionally considered immobile, mainly the High Field Strength Elements (HFSEs) and REEs. This comprehensive study of mineral chemical data is to be complimented by detailed fluid inclusion studies in the future, which can provide deeper insights into the metasomatic fluid composition and mechanisms that drove the episyenitization in the Suomenniemi complex, with potential implications for understanding hydrothermal processes in comparable geological settings.

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035.5

Arc to Backarc: tracking the transition from fluid flux melting to decompression in the Tonga-Lau Region

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The processes of oceanic crust subduction, slab dehydration, and mantle wedge melting in subduction zones remain enigmatic due to overprinting by magmatic processes during crustal ascent, storage and eruption. The elemental transfer from the oceanic crust into the mantle wedge and lithosphere via fluids and melts, and into the upper and lower mantle by residual slab subduction is key to deciphering mass transfer between the mantle, oceanic and island arc crust, hydro- and atmosphere. Mantle melting at mid-ocean ridges and ocean islands is due to decompression melting of variably depleted and enriched mantle, whereas melting in subduction zones is associated with fluid flux melting due to variable volatile input from the subducting slab. The Tonga-Kermadec subduction zone system in the western Pacific consists of a complex mosaic of arc and backarc assemblages, where backarc crust forms simultaneously in different localities as a result of plate reorganization and slab rollback. The Valu Fa Ridge (VFR) and Central Lau Spreading Centre (CLSC) are situated oblique and at increasing distance to the active Tonga island arc. With increasing distance, the depth of the subducting slab increases, allowing tracing of dehydration reactions from about 80 km to >240 km slab depth—a range associated with destabilization of pargasite and phlogopite.

Here, we present new major, trace element, short- and long-lived radiogenic isotope, and volatile data from whole rocks and glasses sampled along the VFR and CLSC. We observe distinct and systematic geochemical trends with increasing distance to the active island arc, such as decreasing ratios of incompatible mobile/immobile trace elements (e.g., Ba/Nb) sensitive to slab contribution, and increasing ratios sensitive to mantle depletion (e.g., Nb/La), which may reflect dehydration reactions in the subducting slab and depletion of the overlying mantle wedge. Short-lived Uranium series disequilibria and volatile contents in glasses are sensitive to changes in the melting process, i.e., flux versus decompression melting. Our data show that the melting regime changes from flux-dominated to decompression-dominated, comparable to mid-ocean ridges, at about 100 km distance between the active arc and backarc. We interpret a stepwise change in melting regime as the result of separation of melting regimes. At distances of less than 100 km, we observe an overlap of the arc and backarc melting regimes, where adiabatically upwelling mantle beneath the spreading axis extracts material from beneath the neighboring island arc. The separation of melting regimes at about 100 km also indicates that the melting area beneath slow spreading ridges (90–65 mm/a) may be 50–80 km to either side of the backarc spreading center. Our results have implications for heat and material flow and accretion processes in the off-axis environment of spreading axes, where erupted magmas commonly preserve less-depleted and more alkaline signatures.

035.6

Sulfur-in-clinopyroxene: can we trace LIP-related volcanic winters from a within-magma perspective?

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Large Igneous Province (LIP) volcanism was a major driver of past climate and environmental disruption, and is implicated in several mass extinctions. These events release large volumes of greenhouse gases (H₂O, CO₂, CH₄) and sulfur dioxide, producing contrasting effects: long-term global warming and short-lived volcanic winters. Historical eruptions (e.g., the 1783–84 Laki fires, the 1991 Pinatubo eruption) show how sulfur-rich emissions can trigger abrupt cooling with societal consequences.

Evidence is growing that similar short-term volcanic winters occurred during LIP emplacement, superimposed on long-term warming (Vickers et al. 2020; Callegaro et al. 2023; Kent et al. 2024). Such transient cooling episodes may have stressed ecosystems and contributed to mass extinction, but their brevity makes them difficult to detect in the stratigraphic record. Sedimentary proxies such as glendonite crystallization are being explored, but their signals remain ambiguous.

We propose a complementary “within-magma” approach for tracing sulfur-rich magmatic pulses capable of generating volcanic winters. Using synchrotron X-ray microfluorescence, we measure sulfur concentrations in clinopyroxene—an early and almost ubiquitous phase in LIPs magmas—and calculate equilibrium melt concentrations with established partition coefficients. Applied to the Deccan Traps (Western Ghats, India), this method reveals that lavas emplaced immediately before the extinction interval are richest in sulfur, whereas later flows are sulfur-poor.

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Assessment of sulfide and chalcophile element behaviour in melt inclusions from the Fagradalsfjall 2021-2023 eruptions, Iceland

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Emission of sulfuric gasses and chalcophile elements are hazards associated with volcanic eruptions. These elements are transported from the mantle source to the surface by ascending magmas. Sulfur concentrations in mantle melts vary according to numerous variables, such as source fO_2 , temperature, pressure, degree of partial melting, and the major element composition of the melt. With strong affinity with sulfides, chalcophile element concentrations in magmas are controlled by processes effecting the partitioning of sulfur during both mantle melting, fractional crystallisation and degassing.

In Icelandic basalts, both magma source and melting processes contribute to the compositional range in parental melts, where low-degree melts are enriched in incompatible chalcophile elements (e.g., Pb) relative to large-degree melts and vice versa for the compatible chalcophile elements (e.g., Cu). As ascending magmas undergo mixing and degassing of volatiles, whole-rock analyses of erupted magmas seldom record the pre-eruptive compositional range or source volatile characteristics. However, melt inclusions (MI) come closer to retaining melt compositions that were present prior to mixing and degassing. Here, we aim to constrain the sulfur and chalcophile element characteristics of endmember magmas that contributed to the Fagradalsfjall 2021-2023 eruptions, which show substantial range in mantle-derived geochemical proxies. To assess source composition and volatile characteristics, we have analysed major elements and SO_3 in ~800 olivine-, plagioclase- and clinopyroxene-hosted MI by EPMA and trace elements in ~200 MI by LA-ICPMS.

The results show that the incompatible element variability in melt inclusions greatly exceeds that in whole-rock data, consistent with pre-eruptive mixing and homogenisation of heterogeneous parental melts. The sulfur and chalcophile element abundances correlate with incompatible element proxies for mantle enrichment. These observations may have implications for behaviour of chalcophile elements and sulfide solubility across different melt fractions.

P35.1

Halogen (Cl-Br-I) composition of magmatic fluids suggests a magmatic origin of salt in Archaean oceans

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High rates of magmatism during the Archaean eon (4.0–2.5 Ga) provided a substantial flux of mantle-derived solutes to Earth's early oceans, including salts. However, Archaean seawater samples—preserved as inclusions in hydrothermal precipitates—have distinctly high Br/Cl and I/Cl relative to the modern mantle source of mid-ocean ridge basalts (Burgess et al. 2020). It is debated whether these differences reflect changes in Earth's mantle composition over time, unknown early halogen sources or sinks, or fractionation of halogens during magmatic processes. One major hurdle in investigating magmatic halogen systematics has been sampling pristine magmatic fluid prior to chemical modifications resulting from interaction with the crust or mixing with seawater. Here, we present new triple halogen (Cl-Br-I) LA-ICP-MS data from high temperature (~660–840°C) quartz-hosted brine inclusions from a gabbroic unit of the ~4 Ma Vesturhorn volcanic complex in Iceland—a modern analogue for magmatic fluid formation processes in the Archaean oceanic crust. Our measurements provide the first empirical Cl-Br-I estimates for magmatic fluids in oceanic environments and offer an opportunity to test melt-fluid partitioning behaviour of halogens in natural samples. The data show that natural magmatic fluids are fractionated toward higher Br/Cl and I/Cl relative to their parental melts, following experimentally determined fluid-melt halogen partitioning trends (Miranda et al. 2025). Notably, the Vesturhorn fluids overlap with the high Br/Cl and I/Cl of Archaean seawater. Together, these observations suggest that the mantle source of Archaean oceanic magmas had a non-chondritic halogen composition by 3.5 Ga resembling modern values, and that Archaean seawater salinity was primarily mantle-derived and supplied by fluids exsolved from cooling mafic intrusions during the genesis of oceanic crust.

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O37.1 (Keynote)

Unravelling fault heterogeneity: a key to linking the geological record to earthquakes, permeability and fluid flow pathways

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Fault zones are far from uniform. Their internal heterogeneity—variations in structure, mineralogy, and physical properties—governs bulk rheology and thus how the brittle crust deforms, how earthquakes initiate and propagate, and how fluids circulate to influence ore deposit formation. Heterogeneous faults are mechanically weaker and less stable than homogeneous ones, producing behaviors from slow-slip events to dynamic ruptures and driving fluid compartmentalization. In the classic “core and damage zone” model, fault cores act as across-fault barriers, while fractured damage zones serve as along-fault conduits. Yet real architectures often deviate from this view, containing secondary structures with distinct hydraulic roles. The coexistence of domains with sharply different hydraulic properties generates heterogeneities and anisotropies in the permeability tensor. Beyond the matrix permeability of the protolith, the secondary permeability of a fault zone depends on the fault rocks, fractures, and damage zones, together with their 3D architecture.

This heterogeneity is not static but evolves through complex deformation histories, leaving an intricate geological record. Central to this record are Brittle Structural Facies (BSFs), structural domains defined by specific fault rocks that preserve the geometry, kinematics, and mechanical properties of fault zones, along with their interaction with changing environmental conditions.

In this talk I explore how we can move beyond static views of fault heterogeneity by explicitly incorporating time. I will present a workflow that integrates multiscale and multidisciplinary observations to reconstruct the evolution of faulting in space and time. Case studies show how BSFs form and change, and how they control seismic style, fluid compartmentalization, and hydrothermal ore deposition. A key method is K-Ar dating of synkinematic clays, which directly dates fault rocks and establishes absolute chronologies of fault activity. By combining structural, mechanical, hydrological, and geochronological data, we can unravel how faults accumulate, store, and release energy over time, and how they guide fluid flow and ore formation.

These insights not only advance earthquake science but also have applied value, from fluid migration models in hydrocarbon and geothermal systems to understanding ore genesis and reservoir integrity for CO₂ and H₂ storage. Ultimately, studying the complexity and temporal evolution of fault heterogeneity provides a dynamic view of crustal deformation, with wide implications across geoscience and society.

O37.2

Structural controls on Ni-Cu-Co mineralisation in the Jotun-Valdres Nappe Complex, south-central Norway: implications for regional critical mineral prospectivity.

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The Nordic regions covering the Fennoscandian Shield hold significant potential for critical minerals. Although tectonic structures are responsible for the origin of many such deposits, structural geology is also responsible for segmenting critical mineral deposits and making ore geometries much more complex. Here we present one such example. The Espedalen Nickel-Copper-Cobalt deposits lie within the lower Jotun-Valdres Nappe Complex of the Caledonian Orogeny. Recent studies have focused on the geometrical and geochronological aspects of the regional geology or on the processes related to the genesis of the mineral deposits. The mineralisation displays typical magmatic textural and compositional features, however, these have been overprinted by deformation. Yet, the extent and origin of the deformation and its influence on both deposit and regional geometries has not been considered in previous studies. We provide new structural and kinematic observations which document the relationship between the sulphide deposits and two separate orogenic episodes and place the mineralisation within a regional tectonic framework. On a map scale, the distribution and geometry of the deposits shows two main patterns: 1) Minor deposits oriented in NNW-SSE linear patterns. 2) Larger, more massive orthomagmatic sulphide deposits forming mappable bodies in ENE-WSW geometries. Detailed structural analysis reveals that type 1 geometries occur within steeply-dipping to vertical strike-slip mylonitic shear zones. The shear zones display mutual cross-cutting relationships with the Ni mineralisation: We observe undeformed mineralisation emplaced within ductile dilation zones in the shear zones, and mineralisation that is deformed within the shear zone fabric. These deposits are rather small (i.e. <1-5 meters) and define vertical, segmented geometries. Type 2 geometries are relatively large (i.e. 5-10s meters) flat-lying zones (20-30 degrees) to the NW that host massive sulphide bodies. These ubiquitously have tectonised margins with top-to SE kinematics which we interpret as tectonically transported during the Caledonian Orogeny. Steep strike slip shear zones associated with Type 1 geometries are found as xenoliths within tectonically dissected blocks in the Type 2 massive sulphides geometries. The age of these steep strike-slip shear zones must be pre-1510Ma, which was interpreted as the crystallization age of the Espedalen Complex. We present a map-based geometric-structural-metallogenetic model for the formation and segmentation of these deposits on a regional scale.

O37.3

The Hardangerfjord Shear Zone: new insights from low-T thermochronological data

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The post-Caledonian Hardangerfjord Shear Zone (HSZ) prominently dissects Western Norway into a northwestern and southeastern part. Onshore to the NE the shear zone extends into the Lærdal-Gjende fault, whereas offshore to the SW it extends into the North Sea towards northern England. This segmentation is also reflected by contrasting onshore low-temperature thermochronological data on either side. Coastal western Norway underwent further structural segmentation during North Sea rifting along N-S trending faults. Apatite fission track (AFT) and apatite (U-Th)/He (AHe) age distributions are strongly governed by this complex network of shear zones and faults.

We present 55 new AFT and 12 new AHe ages between Sognefjord in the N and Haugesund in the S. The data includes two elevation transects in the footwall of the HSZ. Additionally, we include ca. 100 preliminary AFT ages from the thermochronology group in Bergen for better regional coverage. In the hanging wall of the HSZ, apparent AFT ages range from ca. 100 to 360 Ma with a positive age-elevation trend. Corresponding track lengths (TLs) are from moderate to long, indicating protracted Permian – Jurassic cooling. Corresponding AHe ages range from 100 to 220 Ma that also show a positive age-elevation trend. In the footwall apparent AFT ages range from ca. 100 to 260 Ma with short to moderate TLs and AHe data from ca. 80 to 250 Ma. When only samples below 500 m elevation are compared, the hanging wall has statistically older ages than the footwall. Whilst hanging wall samples have relatively long TL with a unimodal distribution, the footwall samples have generally shorter TL and are represented by bimodal TL distributions. The complex AFT TL data of the footwall point to mixed ages with several cooling phases, indicating exhumation by footwall uplift. The youngest AFT ages with corresponding short mean TLs from the innermost Hardangerfjord region and close to sea level are consistent with protracted cooling in the latest Cretaceous, followed by younger rapid exhumation. On a broader regional scale, AFT ages get older from the coast to inland but significant age jumps can be observed across N-S trending faults, related to North Sea opening. Our data indicate a complex tectonic evolution of Western Norway after the collapse the Caledonian orogen. First, the HSZ continued to influence Western Norway as a thermochronological segment boundary followed by further segmentation related to the opening of the North Sea.

O37.4

Tectono-magmatic history of meta-igneous rocks from Nordaustlandet, Svalbard, inferred from $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb geochronology and microstructural analyses

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Situated in the High Arctic, the island of Nordaustlandet is one of the least understood geological terranes on Earth regarding Precambrian and Paleozoic geodynamic processes. Such knowledge is, however, essential to reconstruct the geological evolution of the continental crust surrounding the Arctic Ocean. To elucidate the age of intrusion and tectono-metamorphic activity, the foliation-forming mineral phases, alkali feldspar and zircon grains from a total of 10 samples of meta-igneous rocks from northern Nordaustlandet were dated by $^{40}\text{Ar}/^{39}\text{Ar}$ and U-Pb geochronology. The geochronological study was complemented by a regional compilation of planar metamorphic fabrics and a microstructural analysis. The geochronological results reveal that the emplacement of metagranitoid rocks occurred during the Late Meso- to Early Neoproterozoic era (Stenian - Tonian), followed by Late Caledonian (Scandian) deformation and metamorphism during a Late Silurian to Early Devonian event. Neoproterozoic magmatic bodies intruded at mid-crustal level and were exhumed during the Caledonian orogeny between 420.1 ± 2.3 Ma and 399.9 ± 1.7 Ma. Structural observations allowed us to constrain the mechanisms, intensities and shortening directions of this deformation, which occurred under medium-grade metamorphism. This study indicates that Meso- to Neoproterozoic granitoid rocks, pervasively exposed at the northern coast of Nordaustlandet, were rapidly exhumed during Late Silurian to Early Devonian times, most likely as a consequence of orogenic collapse, and served as host to Late Caledonian felsic intrusions.

037.5

Brittle Deformation Patterns in Southeast Norway

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The bedrock of southern Norway is highly fractured, reflecting a prolonged ~900 Myr history in the brittle regime. Apart from the Oslo Graben, the Fen Complex, and a few dikes and dike swarms, faults and fractures constitute the primary regional dataset for reconstructing the geological evolution of southern Norway. These structures have shaped landscape development and pose major geotechnical and hydrological challenges. Moreover, the tectonic evolution of southern Norway provides an important analogue for the neighbouring Skagerrak and North Sea rifts.

Here, we present new insights into the spatial and temporal patterns of brittle deformation in SE Norway by integrating structural measurements from multiple field campaigns with ML-based lineament mapping and K–Ar geochronology of fault gouge.

Lineament analysis of a novel ML-based dataset derived from a 10 × 10 m DEM reveals a regional predominance of ~N–S-trending lineaments, concentrated in two main zones: along the Norwegian west coast and around the Oslo Rift. ENE–WSW to ESE–WNW lineaments dominate the central part of southern Norway, from Lindesnes to Hardangervidda. NE–SW and NW–SE trends occur throughout the region and locally dominate, but are generally less abundant.

Field measurements in the Kristiansand region indicate two main fault sets: (1) E–W to SE–NW with dip-slip normal displacement, and (2) NE–SW with predominantly dip-slip normal displacement and subordinate dextral strike-slip. The latter includes the Kjevik–Hynnekleiv fault, a major, long-lived segment of the Porsgrunn–Kristiansand fault complex. Structural data from central Telemark show a similar pattern, with an additional N–S set near the Oslo Rift, where N–S faults dominate entirely. In general, field measurements match local lineament trends, although clear discrepancies occur in some areas.

K–Ar dating of ~20 fault gouges across SE Norway indicates prolonged brittle deformation and fluid flow between ~225 Ma and 100 Ma, with a pronounced peak around 200 Ma and a broader distribution between 150 and 100 Ma. A few ages suggest activity during the Caledonian orogeny (440–400 Ma). The K–Ar dataset is complemented by two U–Pb calcite ages from the Oslo Rift (~150 Ma and 65 Ma) and several Ar–Ar pseudotachylite ages east of the Oslo Rift (~375–350 Ma and 295 Ma), coeval with major rift development. No clear relationship emerges between fault ages and their trends. Notably, the timing of dextral strike-slip along NE–SW faults remains unconstrained by current geochronological data. We tentatively suggest that this movement occurred sometime between the Silurian and Permian.

The tectonic framework in Southern Finland and Central Sweden – the importance of regional shear zones in resource exploration

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Hot orogens are characterized by high crustal heat flow, pervasive felsic magmatism, large widths and distributed deformation (e.g., Riller et al. 2012). A key structure for these orogens is the occurrence of anastomosing ductile transpressive shear zones, which are particularly characteristic for partially exhumed regions. Major ductile shear zones in both southern Finland and central Sweden strike E–W and NE–SW and form an anastomosing network, that are formed chiefly by oblique plate convergence, typical for hot orogens such as the Svecofennian orogeny.

Engström (2025) found that the Häme metamorphic belt, southern Finland, and the Ljusdal lithotectonic unit, central Sweden, are similar in terms of metamorphic and tectonic evolution. He also concluded that the Kynsikangas Shear Zone (KSZ) in southern Finland is a major crustal-scale shear zone that formed during the Svecofennian orogeny. The KSZ can be regarded as part of the network of major shear zones that are recognized throughout southern Finland. Structurally, the southern portion of the KSZ connects eastward to shear zones that strike E–W, including the Kankaanranta shear zone and the Hämeenlinna shear zone. Additionally, there appears to be structural continuity of the KSZ with the Kolinummi shear zone in the south, and to the E–W striking Hassela shear zone in central Sweden (Skyttä et al. 2020; Engström 2025). Collectively, these observations reinforce the notion above that major shear zones in southern Finland form an anastomosing network.

The mentioned shear zones are most prominent and, thus, essential for resolving the tectonic evolution of the Svecofennian orogen. State-of-the-art analogue modelling tailored to this orogen is expected to elucidate the deformation kinematics of the shear zone pattern and will be tested against structural ground truth gleaned from individual shear zones. The structural and kinematic analyses of the shear zones and associated faults in Finland and Sweden will help to assess key pathways of fluid flow in crystalline crustal terranes, which increase the potential to form mineral deposits and hold the potential of deep geothermal resources.

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037.8

The Kynsikangas shear zone, Southern Finland: scale-dependent shear zone properties and evidence for fossil slow fault-slip in the deeper continental crust

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Detailed field-based structural examination of the Kynsikangas shear zone (KSZ), a prominent structural discontinuity of the Svecofennian Province, allowed us to better understand well-known structural controversies of crustal-scale shear zones. The controversies include: (1) scale dependence of shear zone properties; (2) reliability of small-scale kinematic indicators; (3) relationship between strain and kinematics and (4) evidence for slow fault-slip in the lower continental crust. The analysis of mineral shape fabrics and deformation kinematics on multiple scales revealed that the KSZ formed by strike slip-dominated, left-lateral transpression under NW-SE shortening. The geometry and intensity of mineral shape fabrics varies significantly with position in the shear zone. Specifically, the shear zone center is characterized by maximal fabric intensity and lineated mineral fabrics indicating significant horizontal stretching. By contrast, planar shape fabrics dominate the shear zone flanks, the patterns of which indicate horizontal displacement in the eastern part and vertical displacement in the west part of the KSZ. Kinematic partitioning of the shear zone is also scale-dependent, with microscopic to dm-scale sense-of-shear departing in part significantly from the kinematics indicated by geometry of asymmetric km-scale fold trains of the shear zone flanks. Thus, small-scale kinematic indicators do not unequivocally portray the regional sense-of-shear and, thus, question their use for identifying shear zone kinematics in general. Finally, dm- to m-scale shear bands and S-C fabrics are pervasive in the lineated shear zone center and indicate horizontal and vertical stretching under frictional-viscous conditions. High-strain variants of these deformation structures resemble scaly fabrics, known from active crustal shear zones formed at low temperature. Along with curved pseudotachylite veins, the shear bands and S-C fabrics may constitute slip transients in a frictional-viscous material formed under high-grade metamorphic conditions. Thus, the KSZ features structural evidence for fossil slow-slip seismic events in the deeper continental crust.

Brittle Deformation and Structural Inheritance in Mesoproterozoic Rapakivi Granites of SW Finland

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The rapakivi granites of Åland and Vehmaa (SW Finland) provide opportunities to study brittle deformation within Mesoproterozoic anorogenic crystalline terranes. Through integrated paleostress analysis, remote sensing, and detailed field mapping, it becomes evident that deformation in both batholiths is influenced by the reactivation of Paleoproterozoic shear zones. These inherited structures seem to have acted as mechanical anisotropies, guiding fault nucleation and propagation during subsequent tectonic phases.

In Åland, two distinct strike-slip faulting stages were identified, associated with WNW–ESE and NE–SW compressional paleostress regimes. Although the granite host rock is mechanically isotropic, the orientation of WNW–ESE trending regional lineaments, aligned with the Sottunga–Jurmo Shear Zone, reflects inherited crustal discontinuities (Ovaskainen et al. 2023; Nordbäck et al. 2024). However, in some areas, outcrop-scale fault orientations deviate from lineament trends, suggesting localized stress field variations or selective reactivation of older structures.

By contrast, the Vehmaa Batholith shows a stronger correlation between outcrop-scale structures and regional lineaments. Brittle deformation in Vehmaa is primarily characterized by NNW–SSE fault zones aligned with the Kynsikangas Shear Zone, along with less continuous ENE–WSW trending structures. Paleostress results from outcrop fault data reveal stress regimes like those in Åland, though with offsets of 15° and 28° in the principal compression directions. These differences underscore the heterogeneity of brittle deformation and emphasize the need for caution when interpreting paleostress data in a regional context. Despite their anorogenic origin and isotropic character, both granite bodies appear to record a deformation history shaped by long-lived tectonic inheritance.

Fracture network analyses from Åland and Vehmaa reveal high fracture connectivity and intensity, indicating that inherited structures not only localized deformation but also enhanced permeability and fluid flow. In Vehmaa, evidence of hydrothermal alteration halos and secondary porosity along faults supports a model in which brittle structures facilitated post-magmatic fluid circulation and mineral alteration. This study contributes to a broader understanding of structural inheritance in continental crust and how brittle structures may enhance fluid flow in otherwise low-permeability crystalline settings.

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Initiation and growth of strike-slip faults and associated damage zone in isotropic crystalline rocks

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Strike-slip faults initiate along small-scale pre-existing brittle fractures, which then grow either by increasing the extent of individual fractures or by linking with other fractures. This process eventually leads to the formation of a fault plane and, later, a fault zone. Fault propagation depends on the lithological composition, structural anisotropy, and heterogeneity of the bedrock. In granitic rocks, faults typically form through dilational or contractional linkage of arrays of extensional en echelon fractures into individual fault planes. With increasing displacement and usually requiring a rotation in the principal stress field, these fault planes evolve into complex zones through the following mechanisms: (i) extensional or compressional step-overs, (ii) formation and coalescence of densely fractured zones between fault planes, or (iii) propagation of the fault by lengthening at its tips, ultimately forming a well-developed fault zone with an eventual gouge-bearing core. While the initiation of fault planes through the linkage of en echelon fractures is widely accepted, the controlling factors associated with the transition from a fault plane to a fault zone in granitic rocks is poorly understood.

In this study we explore the formation of strike-slip fault zones and the associated fracture networks within the damage zones (DZ) of isotropic rapakivi granites. The study area is located on Åland Island in SW Finland, which is well suited for this study due to its well-exposed coastal outcrops. These outcrops enable the use high-resolution 2D orthophotos for detailed structural analysis.

- 1) We show that fault planes within isotropic crystalline granites lacking pre-existing joints, initiate solely through the formation of en echelon fractures. These fractures are linked by contractional cross-fractures, which subsequently evolve into a continuous fault plane.
- 2) The development of the initial faults (containing the individual fault planes and en echelon fractures) further into fault zones occurs dominantly through (i) extensional step-overs involving multiple steps. The linkage between individual fault planes is primarily controlled by the spacing between fault planes relative to their length or maturity. Our study also indicates that rotation of the principal stress direction is not required for the transition from en echelon fractures and to fault zone formation.
- 3) Furthermore, our results show that fault zones may also grow through (i) sub-parallel fault planes interconnected by highly fragmented zones, but rarely by (ii) lengthening of the fault planes. Well-developed fault zones with gouge-bearing cores are observed only in case (i) and in reactivated pre-existing fault zones.

O37.11

Brittle deformation structures and secondary alteration processes observed from meso- to microscale in anisotropic crystalline rocks

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Fracture networks formed by brittle structures, such as faults and joints, serve as 1) zones of weakness within the bedrock, affecting rock stability, and 2) fluid flow pathways, representing one of the most significant contributors to permeability in crystalline rocks. In addition, the permeability can be increased by secondary alteration caused by fluid flow activity. It is well documented that subsequent brittle structures tend to localize and propagate along pre-existing anisotropies, such as foliation and earlier fractures. Moreover, the fracture orientation is scalable in regional to mesoscale. However, studies focussing on meso- to microscale deformation in anisotropic crystalline rocks are limited.

In this study, we will investigate the influence of pre-existing ductile structures on subsequent brittle structures and their scalability from mesoscale to microscale. In addition, we determine how the fracture networks control the secondary alteration. The study is performed on selected outcrops in SW Finland, located in the vicinity of regional-scale ductile shear zones. The outcrops represent different pre-existing structures: i) foliation and semiductile shear, ii) foliation parallel to original beds and iii) homogenous rock without pre-existing anisotropy. All outcrops are studied at three different scales: 1) outcrops (orthomosaic; mesoscale), 2) rock samples from fault zones (panoramic photographs; centimeter scale), 3) thin sections from vicinity of the rock samples (scanned thin section; microscale).

Our results demonstrate that: 1) fault growth follows pre-existing structural anisotropies, such as foliation and semiductile shear zones, particularly at the mesoscale when the angle between these structures and the deforming stress is favourable for fault slip. This is exemplified by an outcrop where a fault propagates only along the most acutely (<25°) oriented foliation planes compared to the main fault. 2) The faults prefer to localize to mica-rich beds and shear zones, rather than in parallel mica-poor beds, underscoring the role of phyllosilicates in facilitating fault propagation. 3) The pre-existing anisotropy controls the orientation of secondary fractures; as the preferred fracture type based on ideally oriented Riedel shear arrays varies between R-fractures in isotropic, and T-, X- and R'-fractures in anisotropic rocks. 4) The fracture networks form similar patterns from the mesoscale to the microscale, which is evidenced by their similar convergence angles and symmetry/asymmetry across the scales. 5) The scalability of brittle structures is not influenced by lithology or pre-existing anisotropy as the geometry of fracture networks remains similar between scales in the studied outcrops. 6) The multiple secondary alteration events are controlled by brittle structures and thus also by pre-existing ductile features.

O37.12

Simulation of channelized flow in crystalline bedrock fractures

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This study investigated fluid flow in crystalline rock samples from southern Finland by comparing laboratory observations with numerical simulations. Laboratory experiments involved injecting a contrast agent into rock samples and imaging the flow using micro-CT scanning. To simulate these experiments, we constructed fracture models for the same samples. Two workflows were tested: fracture network generation and flow modeling with dfnWorks (Hyman et al. 2015), and fracture network modeling with PorePy (Keilegavlen et al. 2021) followed by flow simulation in OpenGeoSys (Kolditz et al. 2012). Simulation results were directly compared to laboratory observations to assess how well the models reproduced the flow patterns observed in the laboratory. This approach addressed challenges in predicting subsurface fluid movement, which is essential for nuclear waste disposal and geothermal energy applications in the crystalline bedrock of Finland.

The preliminary results indicate that the simulations can reproduce the main features of flow observed in laboratory experiments. However, further development of the modeling workflows is required to enable a wider pool of experts, especially geologists, to run such simulations effectively. The use of open-source tools provides a foundation for transparent and reproducible workflows, but additional work is needed to make these approaches more accessible and user-friendly for non-specialists. Continued refinement will support broader adoption and improve the reliability of models for subsurface fluid management, with direct applications both in geological repository safety and geothermal resource assessment.

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P37.1

Structural revisions of the Hopukka quartzite quarry, Northern Norrbotten, Sweden

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The Hopukka quartzite quarry is located in the northern Norrbotten ore province, a region that hosts both iron oxide–apatite (IOA, Kiruna-type) and iron oxide–copper–gold (IOCG) deposits. The nearest known deposit is the Painirova IOA deposit, situated about 2 km east of Hopukka quarry. The quarry exposes mainly Orosirian supracrustal rocks, including mafic to intermediate volcanic units and quartzite, together with intrusions of Lina suite granite. Regionally, the site lies close to two major structures, the Karesuando–Arjeplog Deformation Zone (KADZ) and the Nautanen Deformation Zone (NDZ), both of which are important for controlling mineralization and deformation in the district (Bauer & Andersson 2023).

Continuous exposures at the Hopukka quartzite quarry provides well-suited conditions for detailed structural mapping, revealing bedding, foliation, faults, joints, lithological contacts, and cross-cutting breccias. In the west-central quarry, a face that initially resembled a faulted synform is instead explained as two dominant joint sets dipping WSW and NW, while preserved primary bedding (S_0) consistently dips WSW. The faulted zone, approximately 5-10 m wide and moderately dipping SW, exhibits a 1-2 cm non-cohesive, clay-rich gouge developed in the quartzite contact, as well as associated slickensides. In the northwest, feldspar-bearing quartzite hosts a steeply east-dipping foliation (S_1), with bedding steeper than in the central quarry, close to a volcanic contact mapped by Bauer & Andersson (2023). Widespread breccias cut across the quartzite, often along moderately NW-dipping contacts. These contain sericite-rich clasts aligned with foliation and are locally overprinted by tourmaline, which occurs both parallel to fractures and as later crystallization. Such features indicate multiple fluid events, comparable to tourmaline-bearing assemblages in the Nautanen IOCG deposit area, where they are linked to potassic alteration zones.

The area is known for semi-brittle high-strain zones (Bauer & Andersson 2023) which are exhibited in the surrounding intermediate volcanic rocks examined by exploration trenches in 2025. These may represent the outer parts of brittle faults transitioning inward to brecciated cores and may also resemble regional patterns described by Bauer & Andersson (2023), where doubly plunging folds are crosscut by shear zones. At Hopukka quarry, the interplay of bedding, foliation, brittle faults, and fluid-related brecciation suggests small-scale analogues of these regional processes. Overall, the quarry records deformation and hydrothermal activity acting together, with brittle structures likely serving as conduits for fluid flow – an important factor in assessing mineralization potential in the Norrbotten ore province.

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P37.2

Synthetic ground penetrating radar profiles to study signature features of bedrock surface, weathered bedrock and water-conducting structures in Central Finnish Lapland

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Finite difference modelling (FD) was used to detect four geological/hydrogeological features: 1) the Quaternary sediment – bedrock contact, 2) changes in bedrock lithology, 3) water-conducting structures, and 4) weathered bedrock from the Ground Penetrating Radar (GPR) data. The model domain was set to cover depths of 10 m, and the synthetic modelling was done with 50 MHz antenna with ReflexW software. Three different bedrock types that were underlied by gravelly sand deposits were used in FD models: quartzite, schist, and black schist. The detectability of weathered bedrock was modelled with distinct and transitional contact. The detectability of water-conducting structure was modelled by changing dip and width of these structures. Synthetic FD modelled GPR profiles were compared to real GPR profiles located in Central Finnish Lapland.

Quartzite and schist bedrock surface can be detected as normal polarity interfaces if there is enough contrast of dielectric properties between overlying Quaternary deposits and bedrock surface. Differentiating schist from quartzite is challenging due to low contrast difference in reflected interfaces. Black schist appears as reverse polarity interface if the electric conductivity is high enough (>0.1 S/m). The detection of water conducting structures is plausible if there is enough contrast between adjacent bedrock lithology and overlying Quaternary sediments and water conducting structure, and if the structure is wide enough (>4 meters at depth of 10 m). Additionally, low dip structures are easier to detect than high-dip structures if before-mentioned statements are valid. Transitional contact does not form a detectable interface unless electric conductivity of bedrock is high (>0.1 S/m). Overall, the models indicate that top of clayey weathering or top of weathered black schist with high conductivity may appear as reverse polarity interface on radargram. Otherwise, the weathering zone is challenging to detect. The FD models enabled understanding of signature features regarding hydrogeological structures and can be used to support detection of said structures from actual radargrams.

P37.3

Natural Hydrocarbon Seepage Through Seal-Bypass Systems Above Diapirs in the South Norwegian North Sea

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The North Sea ranks among the world's most productive hydrocarbon provinces, where migration from the dominant Late Jurassic source rocks began in the Late Cretaceous. Only a fraction of the generated hydrocarbons are retained in traps, while a large volume escapes to the surface as natural seepage. In the Southern Norwegian North Sea (SNNS), gas seepage has long been recognized, but recent satellite-based Synthetic Aperture Radar (SAR) analyses have identified abundant oil slicks, including within Block 9/12, the focus of this study. These oil seeps carry significant implications for both exploration and environmental risk.

The SNNS is characterized by Mesozoic rift-related grabens, thick sedimentary successions, and widespread salt diapirs that act as traps and potential fluid pathways through seal-bypass systems. Salt bodies occur in diverse geometries, including towers, walls, collapsed diapirs, and platforms. Faults above diapirs are sometimes linked to seismic chimneys, which can be located directly above or offset from the diapirs, suggesting lateral migration. RMS anomalies at the Top Oligocene level are interpreted as potential hydrocarbon accumulations. Some of these accumulations are related to underlying faults, whereas others are not and instead connect directly to chimneys rooted in deeper strata. The presence of chimneys and tunnel valleys above these accumulations indicates active leakage pathways that may extend to the seabed.

By integrating structural, seismic, and seepage observations, this study aims to reconstruct hydrocarbon migration routes, assess the role of seal-bypass systems, and evaluate the environmental implications of shallow leakage. The outcomes will advance understanding of petroleum system dynamics in salt-influenced settings, support exploration derisking, and inform strategies for secure subsurface storage of CO₂ and hydrogen.

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O38.1

The record of glacial meltwater mega-flood at Mogenstrup, western Denmark

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The Late Pleistocene cataclysmic releases of glacial meltwater left distinct footprint across the Central European Lowland. Deeply incised tunnel valleys, oversized ice-marginal spillways, fields of mega-dunes, and glacial curvilineations carved by rapid drainage events occur along the southern margin of the last (Weichselian) Scandinavian Ice Sheet margin. These meltwater releases contributed significantly to continental-scale sediment re-distribution and landscape re-shaping and may have influenced climate by introducing large volumes of freshwater into the oceans.

Here we present the first record of a major proglacial flood in western Denmark. The flood occurred at the margin of the Weichselian ice sheet during its early deglaciation and retreat from the outermost position around 21,000 years ago. The meltwater, fed through several prominent tunnel valleys, was funneled at the ice forefield and drained along the ice margin to the North Sea generating a field of mega-dunes clearly discernible on LiDAR images. The 47 mapped mega-dunes reach heights of up to 2.2 m (mean 1.1 m) and widths of up to 320 m (mean 138 m) covering an area of approximately 18 km². Excavations, Ground Penetrating Radar surveys and luminescence dating reveal that the mega-dunes consist of poorly bleached parallel- and cross-bedded meltwater sand and gravel, with occasional large-scale foresets indicating palaeoflow directions perpendicular to the dune crests. Estimates of flow conditions utilizing different empirical approaches suggest water depths between 9 and 21 m, flow velocities between 1.5 and 14.5 m/s and water discharges between 82,000 and 1,400,000 m³/s.

Our findings underline the importance of glacial meltwater as a land-shaping and sedimentological agent acting along the margin of a retreating ice sheet.

038.2

Evidence of lakes beneath the Fennoscandian Ice sheet

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Subglacial lakes are increasingly being identified under contemporary ice sheets and ice caps but remain difficult to study in detail through remote sensing techniques or costly borehole operations. Subglacial lake deposits from past records have received little attention because of i) the difficulty of identifying and distinguishing them from other glacial environments, and ii) their low preservation potential, as the fine subglacial glaciolacustrine sediments are sensitive to modification after deposition.

As part of a mapping project covering Tydal municipality, we investigate a $\sim 4 \text{ km}^2$ large area containing glaciolacustrine deposits high up in the mountains (800 m a.s.l.) perched against a mountain ridge in the up-ice direction. Sedimentological and geomorphological observations allow us to identify criteria that can be used to distinguish between proglacial and subglacial lake deposits.

We differentiate between three types of lacustrine deposits that are derived from filling and drainage events of subglacial lakes. Type 1 is characterized by an undulating surface with angular boulders distributed on its top. The surface area covers about 2 km^2 , with a thickness between 7 to 15 m. The deposits are mainly composed of fine sand that sometimes are glaciotectonized. Type 2 constitute smooth hill shaped mounds (7 – 30 m high) and comprise fine sediments with occasional dropstones and minor normal and reverse faulting. Type 3 is characterized by an even surface tilting in the up-ice direction. The sediments are 5 – 30 m thick and covers an area of $\sim 1,3 \text{ km}^2$. The overall stratigraphy is coarsening upwards from layered fine sand and silt to gravel.

We investigate the boundary conditions of the formation of subglacial lakes through modelling the water ponding potential at the ice-bed interface as a function of effective pressure at the bed and ice surface slope. When effective pressures equal ice overburden pressures, we find that subglacial ponding of meltwater initiates at low ice surface slopes (below $\sim 4 \text{ m/km}$). We also find that the ponding of meltwater increases in size as a function of lowering the effective pressure. Low effective pressures reduce the influence of the ice surface slope and allow meltwater to be more readily trapped at the up-ice slope of the threshold, matching the extent of the observed deposits.

Subglacial lake deposits of type 1 and 2 can be explained as a function of variations in effective pressure due to short term cycles of meltwater fluxes. In contrast, type 3 deposits appear more strongly controlled by gradually decreasing ice surface slopes where vertical down wasting dominated during deglaciation. We suggest that all three types of subglacial lakes were active during the Preboreal, under glacial configurations similar to southwestern Greenland today, where subglacial lakes are also reported. Our findings contribute to identifying candidate subglacial lake deposits in similar settings.

O38.3

Glacial erosion on hard beds: the dominance of block removal

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Glacial erosion is conventionally regarded as combining wear (by abrasion) and block removal (by plucking, quarrying, ripping etc.). We adopt two approaches to quantifying these processes on the hard, unevenly fractured bed of the former Fennoscandian Ice Sheet. Firstly, we use the planar sub-Cambrian basement unconformity in Västergötland, Sweden as a datum to identify patterns of glacial erosion since its re-exposure by glacial removal of Early Palaeozoic sedimentary cover. Erosion budgets were dominated by overdeepening of rock trenches and basins. Assuming that abrasion rates are invariant in uniformly hard shield rocks, block removal operated at least four times faster than abrasion. Secondly, we report new cosmogenic nuclide inventories from a site near Forsmark with paired samples from granite gneiss surfaces shaped by (i) sustained abrasion and (ii) combined abrasion and block removal. Combined abrasion and block removal rates in the last glaciation were 34-76 mm ka⁻¹, three times faster than abrasion rates of 9-19 mm ka⁻¹. Samples from the floors of fracture-bounded sockets confirm, with one exception, that missing blocks were removed by the last ice sheet.

Rock block removal has dominated glacial erosion budgets in the two settings. Hence, glacial erosion estimates based on cosmogenic nuclide sampling of bedrock bumps, where abrasion has dominated in the latest phase of subglacial erosion, may significantly underestimate overall glacial erosion rates. Bedrock bumps develop on rock kernels with large block sizes that emerge after selective removal of smaller blocks in the surroundings. As rock block sizes scale inversely with fracture intensity, fracture intensity is revealed as an under-used proxy for predicting rates of glacial downwearing across hard ice sheet beds.

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O38.4

Revised Classification of Glaciofluvial Deposits in Finland

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Sustainable and effective land use, as well as the utilization of geological resources, depend on a consistent and systematic classification of sedimentary units. To support the harmonization of the Geological Survey of Finland's (GTK) national map database of Quaternary superficial deposits, the classification criteria for glaciofluvial deposits have recently been revised. The work builds on earlier geological field mapping of superficial Quaternary deposits (lithological units), as well as previous and ongoing LiDAR DEM-based mapping of glaciofluvial landforms (morpho-lithogenetic units) in Finland. In this presentation, we introduce the updated classification and terminology of glaciofluvial map unit types, discuss their defining criteria, and present representative examples. We also consider the inherent challenges and limitations of this remote sensing-based mapping approach.

038.5

Submarginal ('lodge') moraines: a common yet under-reported type of end moraine

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'Lodge' moraines, originally defined as 'push' and 'dump' moraines, are a type of submarginal end moraine created by incremental deposition of subglacial till at and beneath the margin of the ice. Chamberlin considered lodge moraines to be the most common type of end moraine in the United States Midwest, and moraines in Illinois, Indiana, Ontario and Sweden have been described as forming by this process by subsequent researchers. These moraines typically are asymmetrical, wedge-shaped, with steeper distal slopes with the crest representing the location of the ice margin. Drill holes reveal them to be composed primarily of diamicton interpreted to be subglacial till.

However, the term 'lodge' moraine is rarely used; more often the moraines studied are simply referred to as 'end moraines.' Because of this, lodge moraines (and/or the process by which they form) are not mentioned in the six most widely used textbooks of the last half century. They have likely been commonly neglected in courses on end moraines.

We present lodge moraines as one of the four primary genetic types of end-moraines (along with push, dump and hummocky end moraines). We give examples of end moraines that have been interpreted to be (or are likely) lodge moraines from Illinois, Indiana, Iowa, Minnesota, Wisconsin, Ontario and Sweden. We also discuss the factors why this important moraine type has been neglected.

038.6

Origin of rim ridges and subglacial processes in hummocky terrain of north-central Poland

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Hummocky terrains are characterised by various geomorphological features that typically record processes associated with the downwasting of ice sheets. Common landforms in these areas include ramparts, linear ridges, kettle holes, and ice-walled lake plains. However, the origins of some of these features remain controversial, as they may result from sediment release from stagnant, debris-rich ice or ice-marginal subglacial processes.

This study investigates geomorphology of the hummocky terrain in north-central Poland and the internal composition and structures of rim ridges to decipher their origin. The landforms consist of a circular or oval central part encircled by rim ridges, with a mean ridge height of 1.85 m; the maximum recorded height is 9.21 m (Woronko et al. 2024). The internal composition of the rim ridges was studied at 12 locations, including excavated trenches and exposed escarpments of the ridges distributed across an extensive hummocky terrain.

Each ridge consists predominantly of subglacial traction till interbedded with centimetres-thick fine sand laminae or lenses, indicating episodic basal decoupling and recoupling. Clast fabric measurements reveal a broadly uniform orientation across the study area, often unrelated to the alignment of the ridges themselves. The internal structures consistently show sediments arching into distinct anticlinal forms that mimic the morphology of the rim ridges. Ample evidence suggests that the investigated forms formed in a dead ice environment. It is inferred that water-saturated soft sediments were squeezed into narrow zones between blocks of dead ice due to localised pressure variations thus intriguing rim ridges were formed in response to the dynamic interactions between ice, water and sediment. Overall, these findings emphasise the critical role of sediment saturation and pore pressure distribution in areas where ice is a key component of the environment.

Acknowledgments

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038.7

Subglacial processes of the Pleistocene Witch Ground Ice Stream in the central North Sea

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The North Sea Basin has been covered by ice sheets originating from both the British Isles and Scandinavia at multiple times during the Pleistocene. The Witch Ground Basin in the central northern North Sea is a critical location in terms of interpreting Late Pleistocene glacial to glacialmarine history of the North Sea since it was the location of the Witch Ground Ice Stream that was active on multiple occasions during the Mid to Late Pleistocene. We map mega-scale glacial lineation flowsets corresponding to the changing ice flow direction of the Witch Ground Ice Stream and investigate the sedimentological fingerprint and corresponding subglacial depositional processes of this palaeo-ice stream. We show that sorted sand layers within a primarily massive subglacial traction till represent periodic hydraulic jacking and ice-bed decoupling at the base of the Witch Ground Ice Stream. The most recent ice cover in the Witch Ground Basin (~18 -16 ka) was thought to have been sourced from a localised ice cap over Orkney and Shetland. The presence of chalk clasts sourced from northwest of the Witch Ground Basin described in this study from the stratigraphically youngest till confirms this interpretation. The transition from subglacial to glacialmarine deposition can be differentiated based on a change in colour including mottling and banding, presence of whole intact shells and the increased number of silt and sand lenses. ¹⁴C dating of glacialmarine muds indicate high sedimentation rates that decrease during deposition of Holocene age sandy mud. These results demonstrates a highly dynamic Witch Ground Ice Stream in the northern North Sea during the Late Pleistocene with evolving subglacial hydrology and depositional processes at the ice stream bed that left a distinct geomorphological and sedimentological fingerprint within the Witch Ground Basin.

O38.8

Reconstructing recession of a palaeo-ice stream using high-resolution digital elevation models (DEMs): evidence for repeated surging

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The Irish Sea Ice Stream (ISIS), the largest marine-terminating ice stream to drain the last British-Irish Ice Sheet, was fed from sources onshore on Ireland and Great Britain, and the ice stream retreated onshore during the last glacial termination. This paper presents evidence from central Ireland for the evolution of ice and meltwater dynamics through time as the ice stream margin receded westward across the island of Ireland. A palimpsest landscape of low-amplitude landforms was mapped using high-resolution (1-2 m horizontal resolution) DEMs, accompanied by sedimentological field analysis. Recession of ice into the onset zone was characterised by episodic accelerated ice flow and ice stagnation, accompanied by reorganisation of ice flow trajectories, separation of the ice stream into distinct ice flow units, switches between distributed and channelised subglacial meltwater drainage during retreat.

P38.1

Subglacial geomorphology of Norway: ribbed moraines, formational conditions and localised geomorphological reconstructions

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The subglacial geomorphology of Norway is greatly varying, yet many landforms are under-researched. Ribbed moraines, in particular, are landforms which were formed in subglacial environment of the Fennoscandian, Celtic and Laurentide ice sheets, but their processes of formation are disputed due to the difficulty of reconstructing past subglacial conditions. This is an important gap in present palaeoglaciological research, as understanding bedforms, particularly in reference to a potential bedform continuum, is important for holistic ice sheet reconstructions. Further, the mode of formation of ribbed moraines could provide contextual information on neighbouring features. Here, we present a compilation of works which addresses this gap in knowledge through three complementary papers building a PhD thesis. The data used in this series of works includes high-resolution DEM data, high-quality surficial geological data and ice sheet model data from a numerical ice sheet model of the Fennoscandian ice sheet. In the first study, an automatic machine-learning based method for ribbed moraine detection is developed, which successfully identify ribbed moraines across Norway, including in areas which they were previously unmapped such as south-eastern Finnmark. In the second study, a spatial statistical analysis aimed at deriving formational conditions from present ice sheet models and spatial data is conducted, and from this we determine global factors in ribbed moraine formation including low slope angles, low curvature, high hydraulic head, low hydraulic gradient and slow ice flow velocities. In the final study, we reconstruct the deglaciation of the core region of the Fennoscandian ice sheet, localised around the Norway-Sweden border. Here, we identify primary flow directions during the Fennoscandian ice sheet, and present new insights into subglacial hydrological conditions in the Femundsmarka region of Norway. When combined, these works advance our understanding of ribbed moraine formation, provide new tools and datasets, and identify future paths for study of the Fennoscandian subglacial system.

P38.2

Extreme heat flow and thermal springs at Flade Isblink, Greenland

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While subaerial thermal springs are relatively widespread around Greenland's ice-free periphery, subglacial thermal springs have not yet been documented beneath the ice that covers ~85% of Greenland. Here, we suggest that presumptive subglacial thermal springs play a critical role in maintaining two major subglacial lakes beneath Flade Isblink in Northeast Greenland. The heat sources driving Greenland's thermal springs are diverse and remain debated on a site-by-site basis. Although no recent volcanism has been reported near Flade Isblink, the region may still be influenced by the nearby Yermak Hotspot, located between Greenland and Svalbard. Another plausible heat source is exothermic chemical weathering of pyrite-rich, carbonaceous basement rocks, enhanced by the inflow of meltwater and ocean water, which may account for the anomalous thermogenesis. We estimate that these springs deliver localized basal heat flows of $>960 \text{ mW m}^{-2}$, which is extremely elevated relative to background geothermal flux. These heat flows maintain a locally thawed ice-bed interface in an otherwise frozen-bedded ice cap. Given the sensitivity of ice flow to basal thermal state, subglacial thermal springs can therefore exert a potent influence on local ice dynamics.

P38.3

Internal architecture and allostratigraphic 3D-modelling as tools for characterization of an ice-marginal complex, Southern Finland – implications for groundwater management

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Ice-marginal complexes are important palaeogeographic and palaeoclimatic archives which give information on the flow dynamics of ice sheets (e.g., Winsemann et al. 2018). They deposit at the termini of active or stagnant glaciers as a result of variety of processes such as mass-movements, density underflows or high velocity jets and are characterized by intricate 3D geometry of the sedimentological units (e.g., Ashley 2002). These factors together make classification of these complexes challenging especially when relying solely on geomorphology or even lithostratigraphy.

The studied Huhtainnummi ice-marginal complex is part of the I Salpausselkä ice-marginal formation in Southern Finland (60.716°N, 24.932°E). It serves as an end point for a NW-SE oriented Sastamala-Riihimäki esker, where subglacial meltwater tunnel emerged from beneath the Fennoscandian Ice Sheet (FIS) to the Baltic Ice Lake (BIL). The highest shoreline in the area is ca. 150 m a.s.l. The complex has an area of approximately 68 ha and its elevation varies between 125 m and 140 m a.s.l. The thickness of the Quaternary sediments on the site is approximately 10-20 m. Additionally, the complex serves as a significant aquifer.

In this ongoing study, an allostratigraphic approach is applied in the specification of the internal architecture of the complex. Allostratigraphy is earlier applied in the study of Quaternary sediments by e.g., Lønne (1995). The purpose of this study is to construct an allostratigraphic 3D-model based on GPR profiles, LiDAR scanning, geoseismics, groundwater observation wells and sedimentological analysis through section logging and grain size sampling. Additionally, we define the genetic type of the complex by comprehensive outcrop investigations.

The preliminary results indicate that the Huhtainnummi ice-marginal complex mostly consists of an ice-contact subaqueous fan deposited in the BIL at the turn of Pleistocene and Holocene. Before the beginning of extensive excavating and scientific research of the revealed sections, Huhtainnummi was deemed a glaciofluvial delta which makes Huhtainnummi a typical example of an erroneous interpretation of an intricate ice-marginal complex based solely on geomorphology, and it is likely that similar misinterpretations still prevail in many locations around the FIS area.

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P38.4

Distribution of transient overpressure during rapid deglaciation of the last Fennoscandian Ice Sheet

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The former Fennoscandian Ice Sheet provides an accessible testbed for understanding the impacts of transient overpressure during rapid ice sheet melt. Abrupt warming at the Younger Dryas-early Holocene transition triggered rapid melt, with ice marginal retreat rates of $\sim 300 \text{ m y}^{-1}$. In low relief terrain in Uppland, east-central Sweden, large volumes of meltwater arrived suddenly at the bed, exceeding the drainage capacities of subglacial conduits, and triggering transient development of overpressure ($P_w > P_i$). In this study, we first identify and delimit subglacial drainage pathways by integrating evidence from Digital Elevation Models, air photos and field survey observations with existing map data from SGU. We then add markers for hydraulic damage at the ice sheet bed that include rock hydrofractures, brecciated rock surfaces, and associated boulder spreads, and disrupted roches moutonnées to reveal where subglacial meltwater reached overpressure.

We find that hydraulic damage is largely confined to the floors and sides of former meltwater conduits, including rock trenches, broad meltwater corridors, and esker tunnels. Higher areas of the ice sheet bed generally lack meltwater flow traces, retain a smooth till cover, and carry undamaged precursor rock surfaces. These are interpreted as zones of low volume, distributed subglacial drainage. In the channelised subglacial drainage system, hydraulic damage is unevenly distributed. In some large conduits, hydraulic damage is absent, indicating that large volumes of meltwater were discharged efficiently, with crossing rock trenches acting as drains. Where present, hydraulic damage is often confined to 1- 10 km long segments along conduits. Abrupt onset zones may indicate locations of supraglacial meltwater supply via moulins to the subglacial drainage system.

The extreme conditions necessary for hydraulic damage (instantaneous pressures of up to 8-18 MPa for propagation of new hydrofractures) indicate development over periods of seconds to minutes, with peak pressure developing at rapidly propagating subglacial flood wave fronts. Sharp lateral and vertical limits indicate that hydraulic damage occurred within 1-4 m thick sheets of pressurized meltwater that developed during initial ice-bed separation. Flow then coalesced as conduits opened. Pressurized meltwater flow into pre-existing till sheets caused till, gravel, and sand layers to become dilatant and fluid, with generation of debris and hyper-concentrated flows in conduits, and reworking into till hummocks and murtoo-shaped bedforms.

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P38.5

Fragmented, ice-flow parallel lineations within a glaciated landscape: implications for reconstructing ice dynamics

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High-resolution digital elevation models generated from airborne LiDAR and photography have revolutionised reconstructions of former ice sheet as they allow recognition of low-amplitude, often fragmented glacial landforms that provide evidence for ice and meltwater dynamics. In lowland central Ireland, DEMs reveal a glacial landscape formed during retreat of the last Irish ice sheet between c. 20-15 ka BP. Within this deglacial landscape, lines of low mounds aligned parallel to the direction flow are a relatively common occurrence. This poster examines the characteristics of these features and suggests possible formation mechanisms. The mounds are composed of diamictic sediment and occur both as stand-alone features, and as raised areas within ice flow-transverse ridges. Mounds are both peaked or flat-topped; within an alignment the mounds are of similar appearance. Mound morphology and their relationship to other landforms suggests they form in one of two ways – either as mega-scale glacial lineations, or as crevasse-squeeze ridges.

P38.6

The geomorphology of Þjórsárjökull, central Iceland: streamlined subglacial bedforms and multiple surge impact

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The geomorphology of the forefield of the surge-type glacier Þjórsárjökull, central Iceland, has been mapped for the first time. Þjórsárjökull, an outlet of the Hofsjökull ice cap, consists of three distinct lobes with a total of ~20 km long ice margin. The surge history is not well known with only two documented surges in 1991 and 1994. The geomorphology of the forefield is characterized by multiple, arcuate end moraines some of which are overridden, highly streamlined terrain with drumlins and flutes, and crevasse-squeeze ridges. In addition, ice-cored hummocky moraine and pitted outwash are common. The sediment-landform assemblage is typical of the surging glacier landsystem and indicates a longer history of surges than the documented record suggests. Ground-penetrating radar efforts also reveal an extension of the streamlined subglacial bedforms underneath the present ice-margin. Here we present a preliminary geomorphological map of the forefield alongside previews under the ice.

P38.7

Greenland Ice Sheet behavior over past warm climate periods: A provenance study

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Understanding how the Greenland Ice Sheet (GrIS) has responded to past climate variability is critical for improving predictions of its future behavior and contributions to sea-level rise. As a part of the ChronIce project (Chronicling Greenland Ice Sheet evolution through past warm climates) this study aims to investigate the response of the northern GrIS to past climate forcing by documenting its history of physical weathering and ice–ocean dynamics. Temporal changes in glacial outlets sources (provenances), weathering and erosion in northwest Greenland will be investigated using a unique paleoclimatic archive recovered during Expedition 400 of the International Ocean Drilling Programme. By using the X400 record we will advance the understanding of Arctic ice–ocean–climate feedback mechanisms and improve the accuracy of future projections of glacial mass loss and sea-level rise. Our analytical approach includes examining detrital heavy mineral composition using AQM-SEM (Automated Quantitative Mineralogy – Scanning Electron Microscopy) and LA-ICP-MS (Laser Ablation Inductively Coupled Plasma Mass Spectrometry). The latter also provides single-grain geochronometry as U-Pb dating, enabling precise fingerprinting of ice-rafted debris (IRD) to infer source areas of glacial erosion. Zircon, rutile, apatite, monazite and titanite were detected in the samples and will provide new insights for this provenance study. IRD analyses including grain size and grain texture will be used to reconstruct marine ice margin variability and assess the ice sheet's response to interglacial climate warming under varying pCO₂ forcing scenarios during the Pliocene and Pleistocene. Combined with other detrital and biological proxies, mineral geochronometry on zircon, rutile, apatite, and other datable minerals provides a tool for tracing long-term evolutionary trends in GrIS weathering and ice sheet configuration. Here, we present our initial results.

039.1

A city built on top of problematic rocks – how bedrock can ruin your day

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The city of Stavanger, Norway, is built on phyllite, which is creating problems when extracted for infrastructure and housebuilding. The arsenic concentration in the bedrock mostly exceeds the national action-level for arsenic, 8 ppm; the median concentration is approximately 20 ppm. This exceedance means that extracted phyllite cannot be reused freely at any location. The limitations result in frustrated contractors, who wish to minimize need for costly deposition at landfills and reuse the material, and environmental administrators in the municipality and county that are hampered from making robust decisions due to a lack of geological knowledge coupled with a deficiency in regulations. Could the arsenic concentrations somehow be predicted? NGU has tried to answer that question by systematically investigating whether there is a correlation between arsenic concentration and the phyllite composition, as well as the cause of the high arsenic concentration.

Bedrock field investigations were accompanied by handheld XRF-analyses and sampling for lab analyses. The phyllite unit mainly consists of highly deformed phyllite and mica schist, which vary in characteristics on a meter to centimeter scale. The concentrations of arsenic and other metals vary significantly down to the centimeter scale, regardless of phyllite variety and degree of deformation. Further analyses of the samples using microscopy, SEM and ICP-MS laser measurements of thin sections show that there is mainly a low correlation between the concentration of arsenic and other sulfide-associated metals such as copper, zinc, nickel, cobalt and sulfur. The sulfur content in the samples is generally low (average 0.1%). The results indicate that arsenic is also bound to minerals other than sulfides, particularly chlorite, and very few visible sulfide grains are detected, even in samples with relatively high arsenic content. We hypothesize that As was “captured” in chlorites growing during prograde metamorphism of pyrite-bearing shales.

During the study, paste-pH tests were performed on the samples and approximately 30% of the samples proved to be acid producing. In paste-pH tests, crushed rock samples are combined with distilled water to determine the production of acid from the rock when in contact with water and oxygen. Acid production causes further complications as acid producing rocks, as per environmental law, are categorized as polluted material.

Further work on the lithological unit will entail investigation on the leakage of arsenic and metals from the rock, but also participating in a project studying arsenic-related tumors in cancer patients within the same region.

O39.2

Why do altered metasandstones in Lillesand, Norway, cause spontaneous acidification?

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Spontaneous acid generation from some gneisses in the Lillesand municipality, SE Norway, causes acidification of water bodies, and acute and long-term severe damage to the aquatic environment through extreme levels of leached metals (primarily aluminium). At present, all infrastructure development within the municipality is governed by stringent regulations aimed to minimize environmental impact of acid-generating processes. However, acidification continues to create major environmental consequences in Lillesand because the acid-generating gneisses behave differently than what existing regulations and guidelines are designed for. The main issue is that the gneisses cause spontaneous acidification even at relatively low sulphur contents. In this contribution we try to investigate the geological drivers of acid-generation in the Lillesand gneisses by combining field observations and sampling with geochemical, pH and mineralogical investigations.

The acid-generating gneisses are predominantly biotite-bearing metasandstones of the Lillesand complex, characterized by a pervasive yellow-brown alteration colour, even well below the surface. 740 field portable XRF measurements have been performed, and 65 samples underwent comprehensive laboratory analysis, including NAG-pH, paste-pH, LECO, and XRF. The HH-XRF data showed median sulphur contents of 0,5% S (avg. 2 % S), whereas median LECO results were 0.17% S (avg. 0.5% S). Preliminary NAG-pH measurements show that 94% of the metasandstones have NAG-pH below pH 4 and 42 % below pH 3. 83% of the same samples have paste-pH below pH 6, whereas 7% is below pH 4. Despite the exceedingly low sulphur contents, over 80 % of the Lillesand metasandstones are classified as Medium or High risk according to the NAG-pH vs. paste-pH methodology.

Spontaneous acid generation in the metasandstones indicates the presence of easily solvable secondary sulphur minerals, particularly iron hydroxysulphates such as jarosite and schwertmannite. Preliminary optical microscopy and SEM analyses show the presence of such mineral phases in tectonic fractures and microfractures, as also documented by Hagelia & Huizenga (2025). The widespread appearance of iron hydroxysulphates in the metasandstones, also well below currently exposed levels, indicate that these minerals formed during a phase of extensive oxidation, perhaps related to the evolving Permian-Carboniferous Oslo and Skagerrak rifts or to Mesozoic brittle deformation phases.

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039.3

Acid Sulfate Soils and the Water Framework Directive: Compliance or Case for Exceptions from an Earth Scientist's Perspective

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Acid sulfate soils (ASS) are among the largest contributors of potentially toxic metals to the Baltic Sea. When disturbed through drainage or excavation, these soils oxidize and release excessive amounts of sulfuric acid and toxic metals, leading to acidification, ecological damage, and persistent challenges in achieving the goals of the EU Water Framework Directive. Improving water quality in affected regions requires understanding of both natural processes and human-induced impacts. This distinction is essential for determining what is reasonable to expect from Finland and Sweden in terms of remediation efforts, and what is realistically possible to achieve in order to meet the directive's requirements.

In this study, we will assess the impact of various land use and climate change scenarios on water quality over different time frames in Europe's largest ASS area around the Kvarken Archipelago. Since these soils are a finite source of mobile chemical compounds, they will eventually become depleted. Understanding the timescales over which this depletion occurs is essential for evaluating the long-term trajectory of environmental recovery.

By quantifying the amount of acid-generating material currently stored in the landscape and estimating current release rates, the study provides a foundation for projecting future risks. These acidity reserves will be assessed under different land use and climate scenarios to understand how they may evolve and influence water quality in the coming decades. This includes estimating how much acidity is already formed as well as how much new acidity will be generated and released with a given drop in the groundwater table—whether due to intensified artificial drainage or extended droughts.

This work is carried out within the MASSIW project, funded by Interreg Aurora, and involves collaboration between partners in Finland and Sweden. Participating institutions include Åbo Akademi University, Linnaeus University, the Regional Development Centre in Ostrobothnia, the Geological Survey of Finland, the Geological Survey of Sweden, and the County Administrative Board of Västerbotten. The project aims to provide science-based insights and tools to support effective mitigation strategies and help meet EU environmental targets.

O39.4

Developing acid sulfate soil management for improved water status (MASSIW)

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While being the most productive and expensive farmlands, sulfide-bearing soils that transform into acid sulfate soils (pH < 4) when disturbed by human activity, are regarded as “the nastiest soils in the world” due to the severe environmental problems they cause on water courses. Leaching of acids and metals from acid sulfate soils causes similar environment challenges in both Finland and Sweden. These processes lead to the acidification and contamination of water bodies, resulting in severe ecological consequences such as reduced aquatic biodiversity, impaired fish reproduction, and recurring mass fish deaths. As a result, many water bodies fail to meet the good chemical and ecological status required by the EU Water Framework Directive, posing significant obstacles for implementation of the new EU Nature Restoration Law.

The severe environmental problems associated with acid sulfate soils emerged during the first half of the twentieth century due to intensified land use. Since then, knowledge of these soils has steadily grown through various research efforts. In both Finland and Sweden, various mitigation measures have been developed and tested to differing degrees. Despite these efforts, these problems persist, primarily due to ongoing conflicts between land use priorities and environmental protection goals.

In 2025, an Interreg-Aurora project with the title *Developing acid sulfate soil management for improved water status (MASSIW)* was initiated between the two countries. The aim is to contribute to a solution to this complex and long-standing environmental issue by developing shared, practical, and socioeconomically viable management strategies. This will lead to a win-win for land users and the environment. Hence, the project ultimately supports both local production and helps achieve goals in key EU directives. An important part of the project is that this work will be carried out together with landowners, on local scales. Cross-border knowledge and experience will be exchanged among key academic and governmental organizations. It builds on the synthesis of results from previous projects, integrates social and natural sciences, and closes the gap between academic research and practical fieldwork.

The MASSIW project involves collaboration between partners in Finland and Sweden, and is funded by Interreg Aurora, Västerbotten County Council, the Swedish Agency for Marine and Water Management, and the Regional Council of Lapland. Participating partners include Åbo Akademi University (coordinator), Linnaeus University, the Regional Development Centre in Ostrobothnia, the Geological Survey of Finland, the Geological Survey of Sweden, and the County Administrative Board of Västerbotten.

O39.5

Harmonised marine geological data across Europe for sustainable ocean management: Insights from EMODnet Geology with focus on seabed substrate

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Driven by the increasing demand for reliable marine data to support climate action, biodiversity conservation, and sustainable ocean governance, the European Marine Observation and Data Network (EMODnet) plays a central role in meeting these needs. Since its launch in 2009, EMODnet has delivered harmonized, high-quality marine data from across Europe to support scientific research, policy-making, and sustainable resource management. Through its Central Portal, EMODnet offers open access to thematic datasets covering bathymetry, geology, biology, chemistry, physics, human activities, and seabed habitats.

EMODnet Geology integrates marine geological data to provide comprehensive coverage of European seas, with recent expansion to the Caribbean Sea. The initiative offers harmonized datasets on seabed substrate, sedimentation rates, seabed erosion, sea floor and Quaternary geology, geomorphology, coastal dynamics, geological events, marine mineral resources, and submerged landscapes. Coordinated by the Geological Survey of Finland (GTK), the project is delivered by a consortium of 39 organizations, primarily from the EuroGeoSurveys network, complemented by partners contributing specialized expertise and data.

One part of EMODnet Geology focuses on seabed substrates and their characteristics, including sedimentation rates, seabed erosion, and related information. One of its core data products is a multiscale seabed substrate map, harmonized from national datasets using a modified Folk classification system based on sediment grain size. In support of environmental management, the seabed substrate database includes also detailed information on surface characteristics that influence marine ecosystems but are not solely defined by sediment grain size. These features, such as seagrass meadows, mobile sediments, ferromanganese concretion areas, and bioclastic features provide essential context for understanding of the seabed environment. Such data are vital for habitat mapping, ecosystem monitoring, and informed decision-making in marine spatial planning and resource management.

Over the past sixteen years, EMODnet Geology has become one of the key providers of publicly accessible marine geological datasets, covering extensive areas of European seas and beyond. Its widely recognized methodology ensures consistency and quality across data products. The platform also supports third-party data contributions via EMODnet Data Ingestion (<https://emodnet.ec.europa.eu/en/data-ingestion>). Ongoing development of existing datasets and the introduction of new ones, such as organic carbon content in sediments, geotechnical information and radiocarbon (¹⁴C) measurements, help maintain the relevance of EMODnet data for future environmental management and scientific research.

Acknowledgments

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O39.6

Spatial distribution and morphology of methane-derived authigenic carbonates, or ‘bubbling reefs’ in the Danish offshore environment.

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Methane-derived authigenic carbonates (MDACs) are lithified structures that form due to methane-rich fluid seepage. Carbonate precipitates as a result of anaerobic methane oxidation, facilitated by sulphate-reducing bacteria, and cements loose sediments. The methane generally has a microbial or geothermal origin. MDACs appear all around the world, from deeper to shallower seas, throughout the geological record as palaeostructures and they also form actively in present-day marine environments.

MDACs occur in the Danish marine area, where their exposure is likely linked to (glacio-isostatic) uplift and removal of unconsolidated sediment around the structures. They appear in different morphologies, such as sheets, slabs, pillars or mushroom-like structures. A great variety of fish species spawn, nurse, shelter and feed in cavities and on the hard substrate and these structures. In addition, the hard substrates allow for bivalves, annelid worms, crabs, lobsters, anemones and sponges to live on and are therefore an important habitat for marine biodiversity. They are commonly also referred to as ‘bubbling reefs’. The EU Habitats Directive (HD) and Annex I stress the importance of ‘submarine structures made by leaking gasses’, including ‘bubbling reefs’ (habitat type 1180) as natural habitats and aim to protect them. MDACs are also listed as one of the habitat types in the EU’s Nature Restoration Regulation Annex II. EU’s Nature Restoration Regulation aims to restore nature by 2030 in at least 20% of marine environments. It is therefore important to locate and assess the conditions of MDACs.

MDACs have been documented in the Danish offshore area in Kattegat and Skagerrak. Their spatial distribution and morphology are mapped by geophysical seabed mapping, using a combination of side-scan sonar, multibeam echosounder and sub-bottom profiler data. They are further verified with underwater videos and images acquired by remotely operated vehicle (ROV) or taken by divers. Many of the identified MDACs have been observed in the Trans-European Suture Zone (Sorgenfrei-Tornquist Zone in Kattegat), indicating a link to the subsurface geology. Neotectonics may have activated methane seepage along fault zones. The methane seepage in this area has a microbial origin, as indicated with a distinct stable carbon isotopic ($\delta^{13}\text{C}$) signature and presumably originates from Late Quaternary marine deposits (Jørgensen et al. 1990). However, a clear correlation between the subsurface geology and surface processes remains to be demonstrated. This study aims to provide detailed maps of the spatial distribution and morphology of the MDACs and to assess the potential link of their appearance to the subsurface geology.

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039.7

From Sleep to Deep: Awakening Marine Data through EMODnet Data Ingestion

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Intensifying human activities are placing unprecedented pressure on marine and coastal areas worldwide. Safeguarding marine ecosystems and ensuring the sustainable use of resources depend on effective management, which in turn requires comprehensive and accurate spatial datasets across vast areas. Yet, limited access to marine environmental data, including geological and geospatial datasets, continues to hinder informed decision-making, constrain scientific research, and slow down sustainable economic development.

To address these challenges, the European Commission launched the European Marine Observation and Data Network (EMODnet) in 2009. EMODnet integrates dispersed marine data into publicly available, harmonised datasets that span multiple themes and European sea basins. Today, more than 160 organisations collaborate through EMODnet, assembling, harmonising, and distributing marine data, products, and metadata for both public and private users.

Within this framework, EMODnet Data Ingestion project plays a key role alongside thematic projects such as Bathymetry, Biology, Chemistry, Geology, Human Activities, Physics, and Seabed Habitats. The aim of EMODnet Data Ingestion is to operate a dedicated portal and services that make it easier for data holders—from public authorities, research institutes, industry, and other sectors—to submit new datasets for long-term stewardship in trusted repositories. Once ingested, these datasets are processed, safeguarded, and made discoverable and accessible through the EMODnet Central Portal (<https://emodnet.ec.europa.eu/en>). Participating repositories include National Oceanographic Data Centres (NODCs), Hydrographic Offices, Geological Surveys, Biological Institutes, and other established data management organisations. A particular focus is placed on mobilising datasets that have not yet been incorporated into mainstream data management processes.

The EMODnet Data Ingestion project is implemented by a European network of 46 organisations across 29 coastal countries, including one international organisation. Its geographic reach spans all European marine basins, and its expertise covers every EMODnet thematic area. Most partners are recognised data centres, ensuring scientific robustness and long-term reliability. The consortium also actively involves the coordinators of the EMODnet thematics including EMODnet Geology, which focuses on harmonising and delivering geological data related to the seabed. This collaboration strengthens cross-thematic integration and enhances data flows between domains.

Acknowledgments

The project is coordinated by MARIS (Netherlands), with The Hellenic Centre for Marine Research (HCMR, Greece) serving as scientific coordinator. The project is funded by the European Commission, European Climate, Infrastructure and Environment Executive Agency (CINEA) through contract “CINEA/EMFAF/2021/3.4.10/02/SI2.868290”.

Explore Europe’s seabed geology: <https://emodnet.ec.europa.eu/en/geology>

P39.1

Marine geological studies supporting marine management and conservation efforts around the Åland Island, the Baltic Sea, in the Biodiversea LIFE IP Project

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The Biodiversea LIFE IP project (2021–2029) is Finland’s largest collaborative project to date aimed at safeguarding the biodiversity of the Baltic Sea marine environment and promoting the sustainable use of marine resources. As part of this project, Geological Survey of Finland GTK has conducted marine geological investigations around the Åland Islands to support marine management and conservation efforts.

Here we will describe the geological characteristics of the study area, and the methodologies used in seabed surveys and data analysis. Various seismo-acoustic methods, including Chirp sonars and seismic reflection soundings, along with side-scan and multibeam echo sounders, were employed for field surveys. These surveys provide high-resolution data on seabed geodiversity, sediment distribution, and substrate characteristics. The results indicate that the area is highly diverse and heterogeneous. This information not only improves our understanding of the physical and geological properties of the seafloor but also contributes to assessments of habitat suitability and ecosystem value. We will also discuss the role of geoscience in multidisciplinary marine conservation planning. The results demonstrate how geological insights contribute to a more holistic understanding of marine ecosystems and support science-based decision-making in coastal and marine management.

The Biodiversea LIFE IP project is coordinated by Metsähallitus. In addition to GTK, the project partners include Baltic Sea Action Group (BSAG), Finnish Environment Institute (SYKE), Ministry of the Environment, Natural Resources Institute (Luke), Turku University of Applied Sciences, Åbo Akademi University and Åland Provincial Government. The project has received funding from the LIFE Programme of the European Union. The material reflects the views by the authors, and the European Commission or the CINEA is not responsible for any use that may be made of the information it contains.

P39.2

Marine base maps: Mapping the Norwegian coastal zone

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100 000 km² of coastal Norwegian seabed is managed by local municipalities. The area requirements of fisheries, aquaculture, conservation, leisure activities, industry and infrastructure—often mutually exclusive—are a challenge in marine spatial planning of this coastal zone, where management decisions may have to be made based on limited knowledge of the seabed's physical properties and habitats. The need for better data is pressing.

Modelled on Norway's long-running, interdisciplinary MAREANO programme for offshore seabed mapping, a three-year coastal pilot project was completed in 2022. *Marine Base Maps for the Coastal Zone* was a joint effort between the Norwegian Mapping Authority, the Geological Survey of Norway and the Institute for Marine Research, and produced a suite of detailed, digital thematic maps of bathymetry, seabed geology, nature types and environmental conditions from three pilot areas of 400-500 km². All resulting maps were made freely available and have since found use in many sectors, including municipal spatial planning.

While waiting for a fully funded national coastal mapping programme, NGU has continued mapping near-shore seabed areas in cooperation with local municipalities and counties as well as with other marine actors and stakeholders. So far, we have published maps at 1:10 000 – 1:50 000 scale of around 15% of Norway's coastal areas. Most maps build upon existing high-resolution multibeam echosounder data (MBES bathymetry and backscatter) acquired from the Norwegian Mapping Authority. These data are used for planning field operations by ROV and towed video camera, physical seabed sampling and sub-bottom profiling. Expert marine geologists then interpret the MBES data supported by field observations and other available information and produce thematic vector maps. A typical suite of marine geological maps includes the spatial distribution of seabed sediments (grain size and genesis), sedimentary environment and landforms, as well as analyses of organic and inorganic pollutants in soft sediment and raster models of seabed terrain, slope and backscatter. Together with observations of marine benthic communities and oceanographic data, NGU's sediment maps form the basis of modelled nature type maps following the Nature in Norway hierarchic system (NiN).

NGU's new research vessel, the 24-m long Finnish-built *FF Geologen*, is uniquely adapted to coastal marine mapping. Running on a hybrid power system and equipped with EM2040 and EM710 echosounders, a hull-mounted Topas PS40 sub-bottom profiler, gravimeter, ROV, van Veen grabs and other sampling gear, *Geologen* is an excellent fieldwork platform for NGU's geologists and other users.

O42.1

GEOROC and Beyond: Digital Infrastructure for FAIR and Comparable Geochemical Big Data

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A critical challenge in large-scale geochemistry is the harmonization of global, regional and local datasets, which often vary in analytical protocols, reporting standards, and metadata completeness. Establishing geochemical data and metadata standards as well as best practices and jointly used controlled vocabularies is essential to make such heterogeneous datasets comparable, allowing integration across country boundaries, spatial and temporal scales. The inclusion of detailed metadata (e.g., analytical methods, sample details) and the consistent use of reference materials are crucial for ensuring data quality, reproducibility, and meaningful comparison across studies. Without such measures, the potential of large geochemical datasets in Big Data and AI use-cases would remain limited.

The GEOROC and GeoReM databases are two of the most impactful data resources in the global geochemistry community. They are leading, open-access sources of geochemical and isotopic data that provide access to curated compilations of igneous and metamorphic rocks and mineral compositions as well as reference materials encompassing over 41 million individual data values. The data services support hundreds of new research publications each year across geoscience and related disciplines. To ensure that GEOROC and GeoReM remain sustainable and state-of-the-art resources, the Digital Geochemical Data Infrastructure (DIGIS) initiative is developing a modernized IT architecture and data infrastructure for the geochemical data on samples and reference materials. These efforts will enable improved data submission, discovery, and access while aligning with the FAIR (Findable, Accessible, Interoperable, Reusable) principles.

In this context, DIGIS could act as both a reference framework and a partner for regional geological surveys, including those of the Nordic countries. Establishing shared geochemical metadata standards, vocabularies and workflows for data exchange would create a two-way benefit for the global geochemical research community and the Nordic survey community. By combining global and regional efforts in data collection, curation, and digital infrastructure, the community can move towards a truly interoperable ecosystem of geochemical Big Data beyond boundaries.

O42.2

The hidden impact of data management on data quality traced using simulated Rare Earth Element pattern recognition

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The data life cycle describes the stages of data acquisition, from collecting samples in the field, analysing, processing, publishing, and archiving data so that it might be reused in other contexts. Any errors occurring anywhere in the life cycle thus accumulate in the last stages, specifically data compilations, data repositories, data portals and databases. The presence of “bad” analyses in geochemical compilations is not a new phenomenon. Strategies for handling these bad apples usually involve various “cleaning” procedures to throw out samples. However, those strategies miss important questions to meaningfully remedy the phenomenon: Why do errors occur and how can we identify the type and source of error?

Visually assessing Rare Earth Element (REE) patterns is commonly used as a “cleaning” procedure to check the quality of a rock or mineral sample. The REEs behave systematically in natural rocks/minerals due to their systematic atomic properties resulting in usually smooth normalized REE patterns (excluding well-known Eu and Ce anomalies). Utilizing the REEs, we deep dive into two of the largest public geochemical databases (GEOROC and PetDB) to answer the above posed questions. Our assessment of the REE data in the databases show that the vast fraction of odd looking, zig-zaggy and unnatural patterns track back to data handling and management errors more often than “bad” analyses in the analytical sense. These problems were prevalent in the original published papers too. Common handling errors include offset/switched columns or rows, rounding, normalization, decimal scale/units shifts and rounding.

We are developing a Machine Learning framework using REE patterns that can predict if an error is present and the most likely cause. The training dataset contains the complete collection of samples with originally smooth REE patterns from GEOROC, on which we simulate the different data management errors. To truly capture the patterns, the feature design utilises the principles of compositional data analysis and pairwise log-ratios to capture both the shape of the REE pattern and neighbouring REE behaviour. The resulting model can be applied on any compositional dataset compilation or in other geochemical data repositories or databases that contain REE data. The insights of the model can thus focus the effort to improve geochemical dataset quality by locating and labelling the errors. However, it also highlights the need for a cultural change in the geochemical community to improve data management in the entire data life cycle, a prerequisite for unlocking any potential of Big Data in geochemistry.

O42.3

EarthBank: A FAIR Platform for Integrating Large Geochemical and Geochronological Datasets in Earth Science

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The increasing availability of large, multi-parameter datasets in geophysics, geochemistry, rock physics, and geochronology is transforming how Earth scientists interrogate the Earth. Yet, the integration of these diverse datasets is often hindered by fragmented data storage, inconsistent standards, and limited interoperability. EarthBank has been developed to overcome these barriers by providing a FAIR, relational, and interoperable platform for geochemical and geochronological data.

EarthBank consolidates outputs from multiple laboratories and analytical techniques into a common environment, enabling researchers to move beyond isolated spreadsheets and towards truly integrated digital workflows. The platform facilitates seamless visualization, interrogation, and export of data at scales ranging from individual projects to regional survey datasets with tens to hundreds of thousands of analyses. This provides unique opportunities to work with spatially irregular but geologically representative datasets that are often difficult to combine in traditional frameworks.

Critically, EarthBank's infrastructure supports modern approaches to big data, including statistical modelling, data mining, and machine learning. Researchers can access datasets through intuitive dashboards or via APIs that connect directly to custom analytical pipelines, opening possibilities for predictive modelling and digital Earth applications.

We present examples of how EarthBank has been applied to large-scale geochemical and thermochronological datasets, yielding new insights into tectonic evolution, resource exploration, and Earth system processes. These experiences highlight the transformative potential of structured, interoperable data platforms and demonstrate how public-domain geological survey data can be leveraged for integrative, cross-disciplinary science. Lessons from EarthBank are directly relevant to similar large survey datasets in the Nordic region, where digital infrastructures have the potential to unlock equally powerful advances in Earth research.

O42.4

A Unified Nordic Petrophysical Dataset for Machine Learning and Large-Scale Visualization

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Geological surveys in the Nordic countries have collected large volumes of petrophysical data for decades, including measurements of density, magnetic susceptibility, and remanence (e.g., Airo et al. 2013). These datasets, while publicly available, are typically stored in heterogeneous formats and use varying units, classifications and coordinate systems. The information is also documented in different national languages. This lack of harmonization creates barriers for cross-border analysis and limits the potential of applications such as machine learning and large-scale visualization. The work presented here, performed under the umbrella of the Smart Exploration Research Centre (led by Uppsala University), aims to overcome these challenges by harmonizing and integrating petrophysical datasets from four Nordic countries into a unified resource, and by providing accessible digital tools for analysis.

In collaboration with the geological surveys in Denmark, Finland, Norway and Sweden we assembled and processed over 200,000 petrophysical samples from publicly available national databases. Data harmonization was performed using *Feature Manipulation Engine* (FME), which enabled systematic conversion of units and coordinate systems. Special attention was given to resolving discrepancies in terminology across countries, a common difficulty in large-scale data integration (Bär et al. 2020). The dataset was integrated into a web-based platform that supports efficient querying, visualization, and export. The platform is designed with machine learning and large-scale geospatial analysis in mind, providing standardized data outputs suitable for downstream applications.

The resulting dataset combines petrophysical information from the four countries into a consistent format. Users can access the data via an interactive web interface that allows for geographic and attribute-based filtering, visualization of spatial distributions, and preparation of customized data exports. Early testing has indicated that the dataset is well-suited for training machine learning models, for example in predictive mapping of lithologies.

By harmonizing and visualizing petrophysical datasets across national boundaries, we demonstrate a practical pathway to unlocking the potential of large data resources. The Nordic petrophysical dataset provides a valuable case study in how harmonization can transform accessibility and facilitate new applications.

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O42.5

Does petrophysics reflect lithology? Random Forest modelling applied to Finland's rock geochemical database

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Integrated interpretation of geophysical and geological data requires an understanding of the petrophysical properties of geological units. For applications such as mineral exploration, practical tools for translating petrophysics into geology are still under development (Dentith et al. 2020; Li et al. 2019).

The Rock Geochemical Database (RGDB) of Finland (Rasilainen et al. 2007) comprises 6,544 rock samples that have been systematically collected, analysed, and classified for the entire country. Additionally, the samples have been measured in the Geological Survey of Finland's (GTK) geophysical laboratory for their density, magnetic susceptibility, intensity of remanent magnetisation, and P-wave velocity using methods described by Airo & Säävuori (2013). However, the petrophysical data have not been published. The systematic lithological classification and geochemical data provide a unique platform for evaluating petrophysical parameters within a lithological context.

Large datasets and multiparameter data can be difficult to analyse without machine learning (ML) techniques. This study uses Random Forest (RF) classifier and regression algorithms to analyse the dataset. The two main research questions are: 1) how accurately can petrophysical data reflect lithology, and 2) which key geological/geochemical parameter relationships are associated with petrophysical value ranges. The results highlight the complexity of consistently characterising the petrophysical properties of rock types on a regional scale.

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O42.6

Integrating Petrophysical Data from COSC-1 and COSC-2 for Lithological Classification Through Unsupervised and Supervised Machine Learning

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Downhole petrophysical surveys have become an essential component of scientific and exploration drilling projects driven by advances in technology and increasing affordability of logging equipment. Quantitative analysis of this high-resolution data can significantly enhance lithological interpretation by validating core-based descriptions, extending lithological interpretations across no-recovery zones and providing standardized lithology classification that reduces human bias.

In this study, we explore how petrophysical properties can reflect the underlying geology of drill sections and investigate the feasibility of using machine learning (ML) approaches for objective lithological classification. To achieve this, both unsupervised and supervised ML techniques were applied to petrophysical datasets from two boreholes—COSC-1 and COSC-2—drilled as part of the Collisional Orogeny in the Scandinavian Caledonides (COSC) project, in order to conduct a comparative assessment of ML performance for lithology classification in different lithological sections. The petrophysical properties considered include: density, gamma-ray, P-wave velocity, S-wave velocity, resistivity, magnetic susceptibility, and spectral-gamma measurements (U, Th, K). In addition, lithological classification based on core investigation was utilized to validate unsupervised learning results and as training labels for supervised learning.

For unsupervised learning, hierarchical clustering was applied to both datasets. The optimal number of clusters was determined based on dendrogram analysis and the within-cluster sum of squares (WCSS). Consequently, five clusters were selected for COSC-1 and four for COSC-2. Comparison with core-based lithology reveals separation between felsic and mafic rocks in COSC-1 and between igneous and sedimentary rocks in COSC-2. For supervised learning, four algorithms—Random Forest (RF), Gradient Boosting (XGBoost), Support Vector Machine (SVM), and Artificial Neural Networks (ANN)—were tested. The classification performance is significantly higher for COSC-2, achieving over 90% accuracy, while COSC-1 yielded lower than 60% accuracy.

The results of this study demonstrate the potential of cluster analysis for broad lithological classification, while highlighting how lithological complexity and data quality can influence algorithm performance. In future work, integrating additional geoscientific datasets—including geochemistry and geochronology—with petrophysics could provide deeper insights into compositional variations that are not captured by petrophysical properties alone. Developing such a multidisciplinary approach may enable the identification of specific mineralogical assemblages.



NGWM 2026



The 37th Nordic Geological Winter Meeting was held at the Logomo venue in Turku/Åbo, Finland, 13th–15th January 2026. The event gathered 565 participants from different fields of geosciences. This publication contains the program and 472 accepted abstracts for all the oral and poster presentations held at the meeting. The organizing committee would like to express gratitude to all the participants and authors for their contributions.

Website of the meeting: <https://ngwm2026.fi/>

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