Geological Survey of Finland

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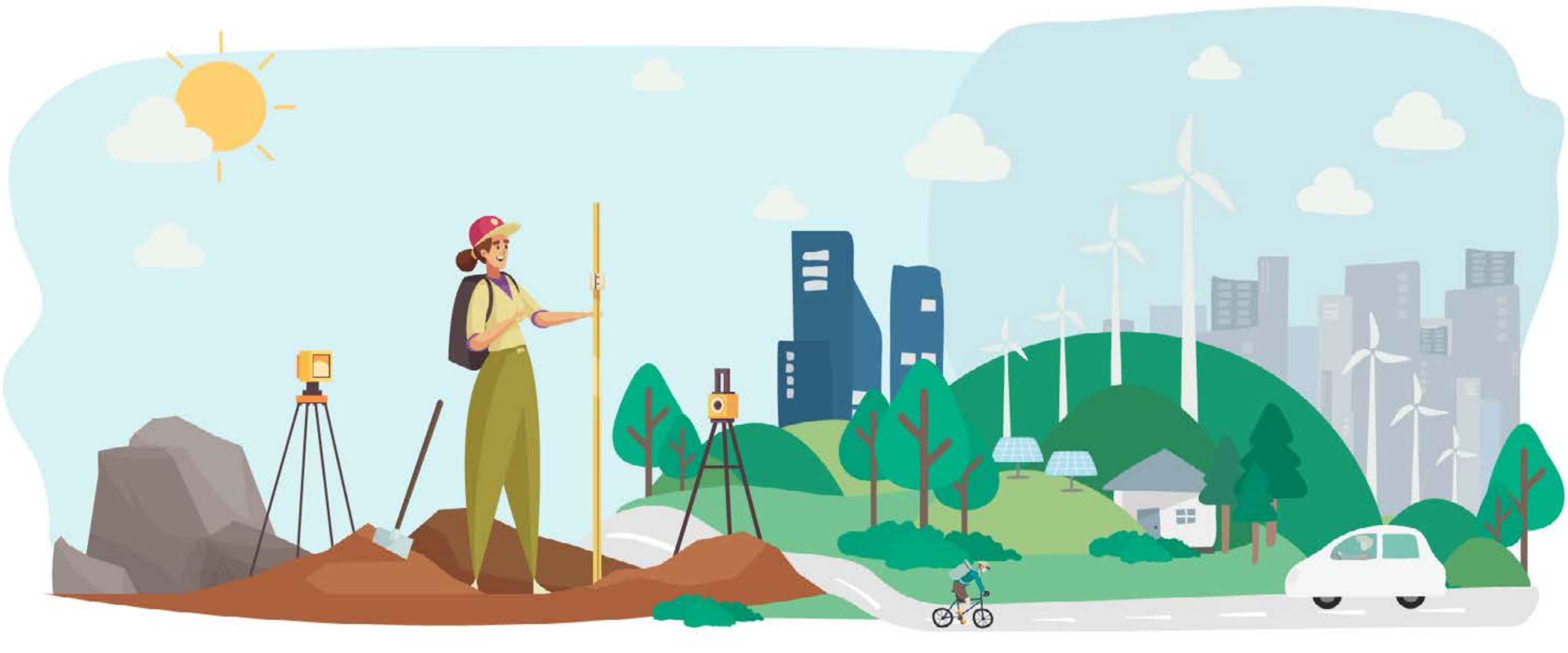
2025 OECD Conference of Mining Regions and Cities: The GeoInnovation Session – 16–18 June 2025, University of Lapland, Rovaniemi, Finland

Abstracts

Vesa Nykänen, Nick Cook and Juha Kaija (eds)

GTK Open File Research Report 39/2025



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Open File Research Report 39/2025

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Abstracts

Edited by Vesa Nykänen, Nick Cook and Juha Kaija

Figures in each abstract are prepared by the author(s) of that specific abstract.

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The EU GeoInnovation Lapland Session, held on 18 June 2025 in Rovaniemi, Finland as part of the OECD Conference of Mining Regions and Cities, brought together experts from academia, research institutions, and industry to discuss critical raw materials within the European Union. The session featured 15 oral presentations and 13 posters, covering topics such as new practices to align exploration with ESG strategies, environmentally friendly exploration methods, and innovations in sustainable mining technologies. This proceedings publication by the Geological Survey of Finland compiles the extended abstracts from the session's oral and poster contributions.

Keywords: mineral exploration, geology, mining, critical raw materials, sustainable development, European Union

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1.4 Poster Session (GeoInnovation Session)

INTRODUCTION

EU GeoInnovation Lapland Session
2025 OECD Conference of Mining Regions and Cities
18 June 2025 | Rovaniemi, Finland

The EU GeoInnovation Lapland Session, held on 18 June 2025 in Rovaniemi, Finland, was a flagship clustering event within the broader framework of the OECD Conference of Mining Regions and Cities. Co-organized by the Geological Survey of Finland (GTK), the Horizon Europe EIS (Exploration Information System) project, and the JTF KAKE (Development of the Extractive Industry in the Lapland, Northern Ostrobothnia and Kainuu) project, together with the Sustainable Minerals Institute, University of Queensland, Australia, the session brought together a lively community of researchers, innovators, and stakeholders committed to advancing sustainable mineral exploration and mining across Europe and beyond.

Set in Lapland—a region responsible for approximately 75% of Finland's mineral exploration based on current exploration licenses—the session served as a dynamic platform for showcasing EU-funded projects and fostering cross-sector collaboration.

Thematic Focus

This clustering session was dedicated to showcasing cutting-edge EU-funded projects that are shaping the future of sustainable mineral exploration and mining. It was structured around three central themes:

- New Practices to Align Exploration with ESG Strategies
- Towards More Environmentally Friendly Exploration Methods
- Innovation Network on More Sustainable Mining Technologies

Highlights from the Presentations

Although the keynote talks of Leena Suopajärvi and Nick Cook were presented in the Main Session of the conference on 17 June, they are included here due to their high relevance.

Dr Leena Suopajärvi, from the University of Lapland, delivered a keynote on the escalating social polarization and rising public resentment toward mining, driven by the cumulative environmental impacts of the industry. She underscored the importance of transparent communication and inclusive dialogue as essential tools for fostering mutual understanding. Central to her message was the role of trust: without it, conflicts risk becoming deeply divisive, especially when local concerns are overlooked or inadequately addressed.

Professor Nick Cook from Sustainable Minerals Institute, University of Queensland, Australia, delivered a keynote address that explored how research and innovation are reshaping the mining industry. His presentation centered on the challenge of meeting the world's growing demand for minerals while upholding environmental integrity and social responsibility. He stressed that one of the most impactful advancements in mining is fostering genuine engagement with all stakeholders – ensuring that collaboration and shared understanding guide the path forward.

The session on 18 June featured a diverse array of presentations, each contributing unique insights and innovations:

Luis Rosendo of Generator Consulting presented the Horizon Europe project CIRAN, which explores how the EU can reconcile critical raw material extraction with biodiversity protection in environmentally sensitive areas.

Cătălina Vrabie from the Horizon Europe project AGEMERA outlined strategies for improving communication and stakeholder engagement in mineral exploration, highlighting tools that build trust and promote transparency in local communities.

Professor Frances Wall, Professor of Applied Mineralogy at the University of Exeter, UK, presented the Horizon Europe project GREENPEG and discussed the role of exploration life cycle assessment and how local communities' perspectives can be considered in mineral exploration projects.

Professor Konstantinos Komnitsas from the Technical University of Crete discussed socio-environmental aspects related to the implementation of strategic projects.

Professor Matthew Laybourne from Queen's University, Canada, presented the Horizon Europe project DeepBEAT, which develops geochemical exploration methods to identify potential for deep-seated critical mineral deposits.

Andreas Knobloch from Beak Consultants, Germany, presented the Horizon Europe project EIS, which has developed a new software tool combining the mineral systems approach with mineral prospectivity mapping. These tools have been tested for critical raw materials potential mapping in the European Union.

Pauliina Liwata-Kenttälä from the Geological Survey of Finland presented the Horizon Europe project MultiMiner, which is developing innovative Earth Observation methods for mineral exploration and mine site monitoring.

Dr. Catalina Hernandez-Moreno and **Dr. Tina Katinka** of the Iberian Sustainable Mining Cluster showcased the Horizon Europe project DEXPLORE, which aims to recognize Europe's potential for hosting deep-land primary critical raw materials by combining new mineral models with advanced exploration and visualization techniques.

Professor Shenghong Yang of the Oulu Mining School, University of Oulu, Finland, gave an overview of the Horizon Europe project SEMACRET, which is developing sustainable exploration methods for orthomagmatic ore deposits.

Professor Saija Luukkanen of the Oulu Mining School, University of Oulu, Finland, presented the Horizon Europe project AVANTIS, which focuses on developing and implementing forensic geometallurgy protocols for the extraction of Ti and V from V-bearing titanomagnetite deposits and V/Ti-bearing mining wastes.

Dr. Anton Koval of Luleå University of Technology, Sweden, introduced the Horizon Europe project PERSEPHONE, which develops methodologies for autonomous and integrated near-mine exploration capabilities to access deep deposits of critical raw materials through hard-to-reach deep and abandoned mines.

Marja Salo of VTT Technical Research Centre of Finland represented the Horizon Europe project CICERO, which applies MSA-based circular hydrometallurgy for sustainable, cost-effective production of NMC cathode materials.

Dr. Fotios Konstantinidis from the Institute of Communication and Computer Systems (ICCS) introduced applications of Industry 5.0 and smart manufacturing in mining, demonstrating how automation and AI can reduce environmental impact while improving operational efficiency.

Dr. Pertti Lamberg presented how Anglo American's Sakatti project in Northern Finland exemplifies a FutureSmart mine by integrating environmental responsibility into every stage of design and operation—from exploration to processing—with innovations that minimize ecological impact and CO_2 emissions.

Dr Merie Kannampuzha from CLIC Innovation Oy presented the Horizon Europe project REMHub—an innovation hub driving European excellence in rare earth elements (REEs) and permanent magnets. REMHub enhances REE supply security, fosters sustainable sourcing, and delivers strategic impact by boosting industrial competitiveness, accelerating green technologies, and strengthening Europe's long-term resilience and innovation capacity.

Kristiina Jokelainen from Iberian Sustainable Mining Cluster, provided valuable insights into the Horizon Europe PERMANET project, a pan-European initiative focused on advancing Rare Earth Element Permanent Magnet (REE PM) technologies. The project aims to enhance the EU's strategic autonomy by developing innovative solutions and integrating both primary and secondary REE supply chains to support sustainable industrial applications.

Poster session

A total of 13 poster abstracts were submitted for the EU GeoInnovation Lapland Session. Below is the complete list of the accepted posters.

Avijit Banerjee and Anton Koval. 2025. MINOTAUR: A Revolutionary Approach to Sustainable, Smart, and Rapid Mineral Exploration.

Juha Kaija, Jochen Kamm, Tuija Luhta, Tero Niiranen, Kathryn Cutts, Graham Hill, Mathieu Darnet, Sam Whittlesey, Michael Becken, Capucine Pineau, Luis Albardeiro, Romain Chassagne, Christian Sippl and Peter Sorjonen-Ward. 2025. UNDERCOVER – redefining the deep mineral exploration.

Anna Kantola. 2025. THE SOCIAL IMPACTS OF MINING: A follow-up research in Northern Finland.

Lumiere M. Katoj and Andrej Kraslawski. 2025. Responsible mining for energy transition; ESG challenges and opportunities in Africa.

Juho Kupila, Jouni Pihlaja, Hannu Panttila and Juha Kaija. 2025. Development of the mining sector in Lapland, Northern Ostrobothnia, and Kainuu.

Luodes Nike, Farahnakian Fahimeh, Karlsson Teemu, Toni Eerola, Ana Cláudia Teodoro and Maria Mavroudi. 2025. Use of remote sensing along mining life cycle – Technological, social and policy aspects.

Nikolas Ovaskainen. 2025. Critical raw material overlap with protected areas by country and commodity.

Niina Paasovaara, Samuel Hartikainen, Sirpa Peräniemi, Hannu Kuopanportti and Shenghong Yang. 2025. Sustainable comminution and enrichment processes of minerals through the new innovative CCC method.

Mia Pursiainen, Juha Hämäläinen, Jari Jäntti, Jari Sonninen, Laura Antikainen, Irina Levchuk, Tatiana Samarina, Viivi Vepsäläinen and Kari Kuuspalo. 2025. A case study of sulphate removal from mine water by nanofiltration. Focus on water recycling.

Jarkko P. Räty, Kaisa Turunen and Maarit K. Hattuniemi. 2025. The AWE - Arctic Water Excellence project: Strengthening innovation based on regional spearheads in the water sector and profiled cooperation in the Eastern and Northern Finland.

Pertti Sarala and Heikki Bauert. 2025. Development of enhance research and technical capacity at the Geological Survey of Estonia.

Inka-Mari Sarvola, Minna Salo and Mona Arnold. 2025. Opportunities and challenges of adapting innovations in the mining industry.

Minoo Yadi, Samuel Hartikainen, Niina Paasovaara, Satu Pitkäaho, Harri Haapasalo, Shenghong Yang, Riitta Keiski and Nora Jullok. 2025. Rare earth and magnets HUB (REMHub): The role of UOULU towards sustainable EU REE supply and clean energy transition.

Impact and Outlook

The EU GeoInnovation Lapland Session was more than a showcase for various projects—it was a catalyst for future collaboration. Through oral presentations, poster exhibitions, and interactive discussions, participants explored synergies, shared best practices, and built connections across disciplines and regions. The session reinforced the importance of innovation ecosystems and demonstrated how Lapland, with its unique blend of natural resources, cultural heritage, and scientific excellence, can serve as a model for sustainable mining regions worldwide.

We are pleased to present this collection of abstracts as a testament to the innovative spirit and collaborative energy driving Europe's transition toward a greener, more resilient mining sector.

Organising committee

Professor Vesa Nykänen, Geological Survey of Finland

Professor Nick Cook, Sustainable Minerals Institute, The University of Queensland

Juha Kaija, Geological Survey of Finland

ISSUES OF (DIS)TRUST IN BUILDING ACCEPTANCE OF EXTRACTIVE INDUSTRIES IN NORTHERN FINLAND

by

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Issues related to mineral exploration and mining are of immense significance to locals living near to such operations. This is attested by a survey conducted by the University of Lapland and the University of Oulu in the AGEMERA project (AGEMERA 2025) concerning three municipalities in Northern Finland, Kuusamo, Posio and Rovaniemi. 851 people responded to the survey in February 2025, which was distributed through the website of the University of Lapland, local media outlets and social media. The responses covered the study area well, as 34% of the respondents reported Rovaniemi as their home municipality, 27% reported Kuusamo and 8% reported Posio. Almost a third of the respondents, 31%, did not live in the area, but had some kind of connection to it, (e.g. family roots or a second home). This highlights the fact that people can feel like "locals" even if they do not reside in the area permanently and can demonstrate an interest in contributing to or staying informed about local developments. Most of the respondents were highly educated with at least a higher secondary degree, employed, and aged from 16 to 87.

The survey participants were asked, what is their stand towards mineral exploration and mining in their home region (Fig. 1). Since the respondents had varied

	Attitude towards mining or mineral exploration verbalised as	I approve of mineral exploration in my home region	I approve of mining in my home region
Completely disagree (n=310)	Reject	36%	44%
Somewhat disagree (n=185)	Oppose	22%	20%
Neither agree nor disagree (n=29)	Neutral	3%	3%
Somewhat agree (n=132)	Accept	16%	15%
Completely agree (n=187)	Approve	22%	17%
I don't know (n=3)	N/A	0%	0%
No answer (n=5)	N/A	1%	1%

Fig. 1. Attitudes towards mineral exploration and mining (n=851).

connections to the study region, it is evident that there is no one shared understanding on the concept of "home". Still, the responses can be interpreted to portray broadly the current attitudes towards mineral exploration and mining in the given region. 64 percent of the respondents were mining critics (those, who reject or oppose mining in their home region), 32 percent were mining supporters (those, who approve or accept mining in their home region), and 4 percent did not have a clear opinion on the matter or did not answer the question. The results cannot be generalised, since the survey – as usual – is answered by those who have an opinion on the topic. Thus, it is possible that the majority of residents in these three municipalities do not have a strong clear opinion on the matter. In general, mineral exploration is considered as a few percentage points more acceptable than mining, but clearly, in people's minds, the two are connected – the goal of exploration is, after all, to find ore that can be exploited. In addition, mineral exploration is a topical issue in the region, since there are no active mines in the study region.

In this approach, we chose one aspect that explains attitudes towards mineral exploration and mining, namely trust. Trust is fundamental foundation of complex societies and communal activities and it is continually being expanded: you have to trust to institutions and organisations, that the authorities will do their job according to the law, that politicians will do what they promise, and that companies will be responsible for environmental issues, for example – without certain knowledge that this will actually happen. (Luhmann 1979, Sztompka 1999.) According to the basic idea of the concept of trust, when there is no complete knowledge or certainty that things are working as agreed and correctly, trust in companies, decision-making, and authorities is a significant factor in the formation of mining attitudes.

First, mining critics do not trust mining or mineral exploration companies at all. A maximum of one percent of them trusts these companies very much or relatively much. It is not possible to answer, whether mining criticism is due to a lack of trust in the companies or if the lack of trust is a result of mining criticism. However, there is a strong connection between criticism and lack of trust in the companies. The message to the industry is clear. Practically almost all mining critics argue that mineral exploration companies do not listen to the concerns or wishes of the locals, they are not open and transparent in their operations, and they do not respect local people. Less than half of mining critics have been in contact with any mineral exploration companies which clearly indicates a lack of communication. Approximately 40 percent of mining critics have been in contact with at least one mineral exploration company, whereas the corresponding percentage is about 60 for mining supporters.

However, the supporters of mining and mineral exploration are partially critical towards companies' performance as well. It is noteworthy, that as many as 71% of those accepting exploration in their home region disagree with the statement "Mineral exploration companies are open and transparent about their operations". The trust towards mineral exploration and mining companies is higher only among those who approve mineral exploration and mining in their home region.

Second, trust in political bodies on national and European Union level is low among mining critics. Among those who fully reject mining, 70% trust the EU relatively little or very little. On the other hand, 59% of those who oppose mining have little trust in the EU. Distrust towards national decision-making is even higher: 84% of those who reject mining and 80% of those who oppose mining do not trust national decision-making. The lack of trust stems from a feeling of powerlessness: three-quarters of mining critics think that the authorities do not take the concerns of local people seriously and argue that local peoples' opinions do not have much of an effect on the decision-making concerning the extractive industry. It is worth noting that the majority of those who accept mining, 58%, also think that local people do not have a say in decision-making related to mines. Only those, who approve mining believe that the opinions of the citizens are heard in decision-making of mining, 58% of them think so.

In general, mining supporters seem to trust more companies and authorities in the field. Those who are critical of mining, listen more to environmental organisations and, for example, the Reindeer Herders' Association, which is concerned about the future of their livelihood in northern areas. Land use in mines restricts the free grazing of reindeer and negative environmental impacts such as dust, noise or increasing traffic can endanger the survival of reindeer herds. Trust towards scientific community is relatively high among all respondents, although trust seems to be a bit lower among those, who have a strong opinion concerning mines. As for the media, trust towards traditional media is clearly stronger than trust towards social media. Trust towards different actors is presented in Figures 2 and 3.

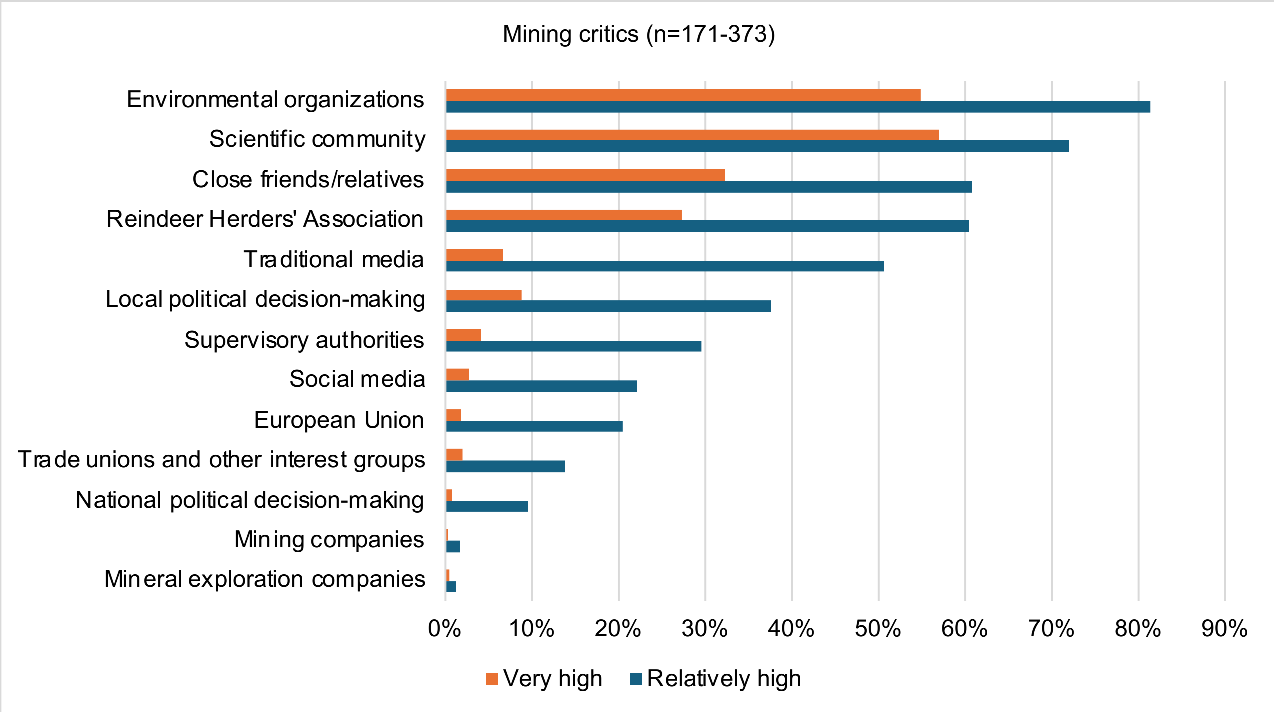

Fig. 2. Trust in different actors among mining critics.

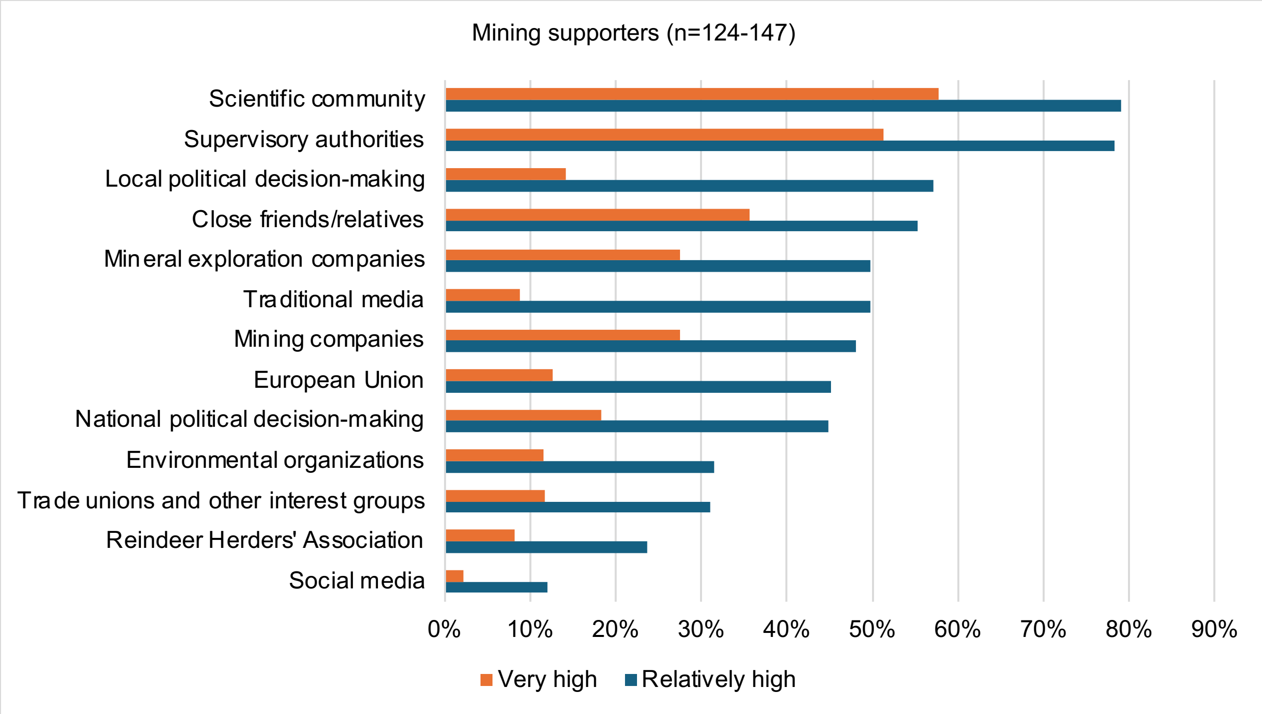

Fig. 3. Trust in different actors among mining supporters.

Without knowledge, trust becomes even more significant. The survey results indicate suspicion among local people towards companies, media and decision-making. Since mineral exploration and mining are subject to intense political debate, people may consider different actors as ideological or think that they have vested interests when deciding on these issues. This may explain why there are notable differences between mining supporters and mining critics. Traditionally, the supporters have a strong trust towards statutory authorities, while the critics have a stronger reliance on environmental organizations rather than authorities. Nevertheless, the data from both sides indicates a clear need for scientific knowledge about the impacts of mining industry to local environments.

Looking ahead, mining critics believe, that trust in the future is built on nature and for example nature-based tourism. Mines are jeopardising this future vision through their environmental impacts and risks. On the contrary, mining supporters see the industry diversifying the economic structure of the region. They do not believe that the future can be built on tourism alone and point out that mass tourism also has negative environmental impacts. A shared concern is depopulation, echoes of past decades about the declining development of sparsely populated areas are present.

To sum up, exploration companies still have work to do to gain the acceptance of local people in Northern Finland. It is also worth considering why local people feel powerless in decision-making related to mines, despite the environmental impact assessment procedure and permit process. If companies do not provide information about their operations and the legal regulatory framework is perceived as pro-mining, it is no wonder that the voices critical of mining are gaining strength among local people. Mining divides people's opinions and, for example, their visions of the future are different. There is no compromise – the alternatives to mines are yes or no. Taking this and the collected data into account, further conflicts related to mines may be expected in the future in Northern Finland. These conflicts have potential to be intense and divisive if local concerns are not properly addressed and resolved.

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COMMUNITY DEVELOPMENT AGREEMENTS – A BLUEPRINT TO RECONCILE MINERALS EXTRACTION AND NATURE PROTECTION IN EUROPE

by

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The European Union (EU) is confronted by a complex governance challenge in securing critical raw materials (CRM) while upholding environmental protection standards. The EU-funded CIRAN project investigates the evolving raw materials governance framework, particularly the Critical Raw Materials Act (CRMA) and its implications for environmentally protected areas. With approximately 85% of known European CRM deposits situated within or adjacent to environmentally protected regions, and in the absence of clear decision-making protocols to balance protection with extraction imperatives, the CRMA implementation presents significant ethical dilemmas for permitting authorities.

Our research examined a fundamental question: how might biodiversity protection be reconciled with securing mineral resources essential for Europe's economic stability and quality of life?

The methodology comprised systematic analyses of mining operations in proximity to protected areas across nine European countries, utilising the DPSIR (Drivers-Pressures-States-Impacts-Responses) framework to evaluate policy mechanisms, such as the EU Green Deal. Additionally, we conducted consultations with five distinct communities residing near environmentally protected areas throughout the EU.

Contrary to assertions in contemporary narratives characterising mining projects as inherently destructive, our findings demonstrate that mineral extraction is both, feasible in protected areas and socially acceptable across all studied cases. While current regulatory frameworks do not categorically prohibit mining operations in protected zones, administrative impediments—notably understaffed agencies, politically motivated regulatory interpretations, and protracted permitting procedures—engender considerable delays.

The lack of public acceptance emerged as the foremost barrier to effective CRMA implementation. Resistance typically emanates from perceived disconnections between EU-level policies and local interests, corresponding with broader Eurosceptic sentiments and mistrust in institutions. Successful mining projects consistently exhibited three characteristics: comprehensive environmental impact assessments, effective stakeholder engagement, and robust post-mining planning.

Community Development Agreements (CDAs) emerged as a promising mechanism to address the public trust deficit and facilitate equitable distribution of burdens and benefits. These formal tripartite arrangements between governments, mining companies and communities, focused on long-term regional development and have successfully reconfigured social contracts in various contexts. World Bank research indicates that effective CDAs mitigate non-technical risks, enhance societal acceptance, reduce conflict, and foster cooperative development through three essential components: a negotiated agreement formalising stakeholder rights and obligations; a representative monitoring body with sufficient resources and authority; and an effective dispute resolution mechanism including arbitration.

Community Development Agreements transcend traditional administrative processes by establishing shared visions with clear accountability for all parties, rendering them particularly valuable for projects in ecologically sensitive areas. Their impact on local and regional development is profound, harnessing mining operations as catalysts for sustainable territorial development. By facilitating meaningful local participation in decision-making, CDAs establish pathways for communities to obtain direct benefits from resource extraction via infrastructure development, educational opportunities, healthcare improvements, or economic diversification – according to their expressed preferences. This approach addresses the gap between local concerns and EU-level policy priorities, thereby establishing a more robust foundation for societal acceptance of CRM mining projects. The tripartite structure ensures benefits align with long-term regional development objectives, transforming what might otherwise be perceived as mere resource extraction into integral components of sustainable local economies.

TOWARDS RESPONSIBLE CRITICAL RAW MATERIAL EXPLORATION: THE HORIZON EUROPE AGEMERA PROJECT

by

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Europe's transition to a low-carbon and digital economy requires secure and responsible access to critical raw materials (CRMs). The Horizon Europe-funded AGEMERA project (2022–2025) has responded to this challenge by developing an integrated approach to mineral exploration combining geoscientific innovation, stakeholder engagement, digital tools, and education. AGEMERA has demonstrated how technical and societal dimensions can be aligned to support Europe's raw materials strategy. (Holma et al. 2022, Joutsenvaara et al. 2023).

At its foundation, AGEMERA has built a comprehensive, cross-border understanding of Europe's critical raw material potential by integrating open-access legacy data with newly acquired field, laboratory, and modelling results. The project has updated and refined geological interpretations and mineral system models in diverse geological settings. This includes the development of 3D computer models for key sites such as the volcanogenic massive sulphide (VMS) deposit at Mina Concepción in Spain and the karst-hosted bauxite district in Posušje, Bosnia and Herzegovina. In parallel, novel laboratory data and structural models were generated for porphyry copper (Bulgaria), stratabound copper (Poland), and other CRM-rich systems in Finland and Zambia. All datasets were harmonised and stored in an EGDI-compatible database, improving Europe's digital infrastructure for raw materials exploration (Joutsenvaara et al. 2023).

Equally important, AGEMERA has placed strong emphasis on community perspectives and awareness-raising. Public perception surveys and interviews in Finland, Estonia, Poland, Germany, and Zambia revealed widespread recognition of the need for CRMs, alongside concerns about environmental risks, land use, and long-term benefits (Suopajärvi & Tulilehto 2023). Educational content developed through university partnerships and public outreach events has also promoted awareness of responsible sourcing and introduced tools such as the UNFC and UNRMS frameworks as part of university of courses to build future capacity in sustainable resource governance (Joutsenvaara et al. 2023).

In parallel, the project has successfully tested a suite of innovative, non-invasive exploration technologies. These include muography, passive seismic, and drone-borne electromagnetic methods, which were deployed at selected trial sites across Europe and Zambia. These methods demonstrated their potential to improve subsurface imaging while significantly reducing environmental and social disturbance making them suitable for both early-stage and sensitive exploration contexts. (Holma et al. 2023, Joutsenvaara et al. 2025).

To integrate these multidisciplinary outputs, AGEMERA developed the AGEMERA AI platform, which is digital environment for visualising geoscientific, environmental, and social data. The system uses AI Knowledge Packs and natural language tools to support exploration targeting and decision-making under ESG constraints. As a cloud-based, user-oriented platform, it represents a key step toward more transparent, intelligent, and responsible data use in exploration. (Stimac Tumara & Matselyukh 2024)

With its activities now concluding, AGEMERA demonstrates that critical raw material exploration can be both innovative and socially responsive. The project offers a blueprint for balancing Europe's strategic autonomy with local acceptance and environmental stewardship.

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GREENPEG PROJECT: EXPLORATION LIFE CYCLE ASSESSMENT AND LISTENING TO COMMUNITIES

by

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The GREENPEG Innovation Action (Grant number 869274) made a new exploration toolkit for rare metal (including lithium) and high purity quartz pegmatites. The team, from 13 organisations, including academia, industry and a geological survey, developed remote sensing, geophysics, geochemistry and mineralogy techniques at province, district and prospect scale (Fig. 1). The small size of many European (and other) pegmatite bodies makes them challenging to detect. Combining a deep research knowledge of pegmatite geology with expertise in exploration techniques was instrumental in creating the novel toolkit, which is now published and freely available (Müller et al. 2025).

Environmental, social and governance considerations are essential elements of an exploration campaign, right from the first stages of desk study, and are included in the toolkit. The GREENPEG project developed a life cycle assessment (LCA) protocol to compare the environmental impacts of various exploration techniques. Likewise, our social studies also concentrated on the exploration stage, building on previous research, such as Lesser et al. (2021), Suopajärvi et al. (2019). We chose not to use a social LCA and instead carried out surveys and qualitative interviews, listening to the views of communities in two of the GREENPEG study areas at Hamarøy, Norway and Wicklow, Ireland, as well as surveys after helicopter-borne electromagnetic exploration in Cornwall, UK and Barroso-Alvão, Portugal. We also carried out a desk study of the pathways to production and 'social license to operate" of seven lithium exploration and mine development projects in Europe. The full results of these studies are written up as three deliverables (Greenpeg 2023, Greenpeg 2024a,b). We did not carry out primary research on governance but the background to the operating conditions and regulations at the GREENPEG study sites was reviewed in an early project deliverable

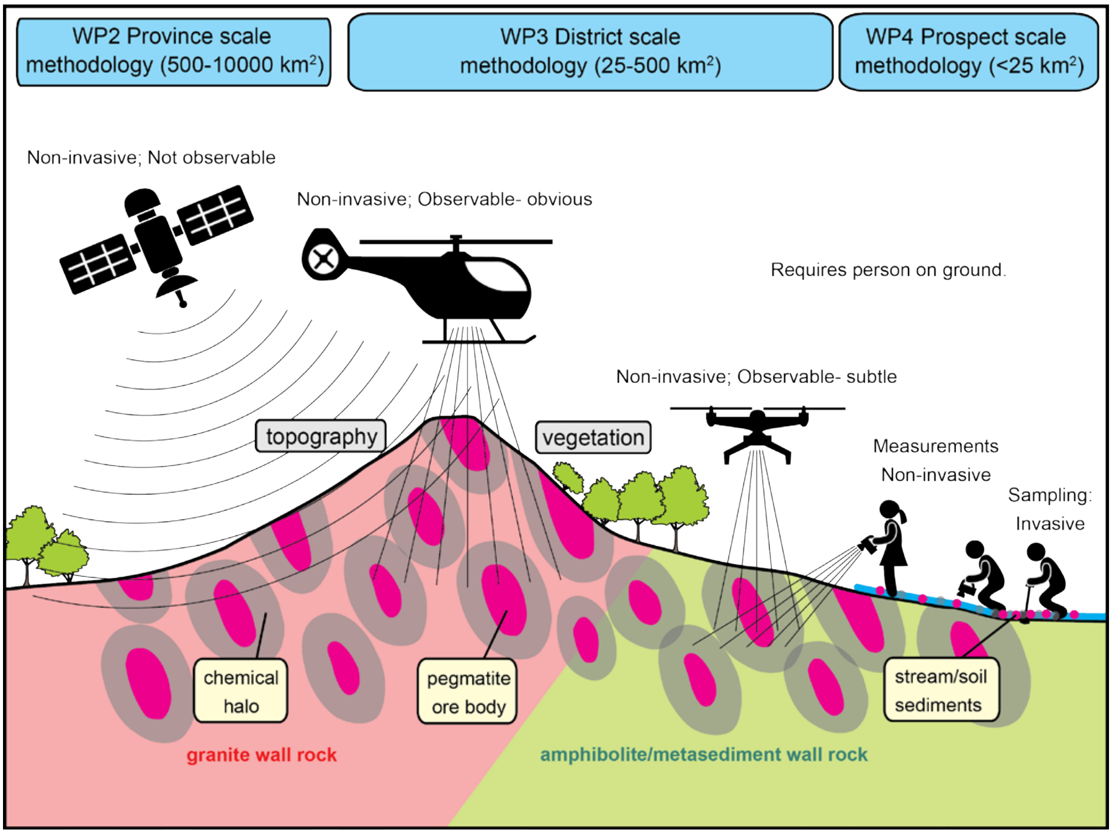

Fig. 1. Exploration techniques in GREENPEG, adapted from an original diagram by Axel Muller. Different work packages (WP) concentrated on the different scales of exploration: province – prospect (Greenpeg 2021).

LIFE CYCLE ASSESSMENT OF EXPLORATION TECHNIQUES

Life Cycle Assessment (LCA) is a systematic methodology for evaluation of the environmental impact of a product, process, or activity throughout its entire life cycle or in selected parts of the life cycle. Here we concentrated on the impacts of the actual exploration activities, which have received very little consideration by LCA. We used the European Commission-Joint Research Centre – Institute for Environment and Sustainability (2010, 2011): International Reference Life Cycle Data System (ILCD) recommended methods, including updates made during development of the EC Product Environmental Footprint initiative, and used inventories from the GREENPEG deployments, where possible. The main challenge in applying LCA to exploration techniques is that it is not easy to define a functional unit or reference flow owing to the diverse range of techniques and different spatial scales. We used combination functional units, chosen to represent each technique over a particular area, that ranged from 9600 km² (Province scale) to hectare (Prospect scale) or per 350 m deep hole (Focussed prospect scale for drilling). Results were combined to calculate scenarios for a whole campaign in 16 impact categories. The campaign demonstrated that the fossil fuel impacts of drilling are the most impactful activity (Fig. 2). Travel to and around the site is also a key (Fig. 2, Table 1). Helicopter impacts, which would be expected to be large, can be halved or divided by a third by flying with two or three combined detectors (Fig. 2). Sharing data also lowers environmental impact, for example by using libraries of satellite images or geophysics. The impacts of prospect-scale techniques are mostly low but the carbon footprint of argon use in geochemical analyses can be surprisingly high (Table 1).

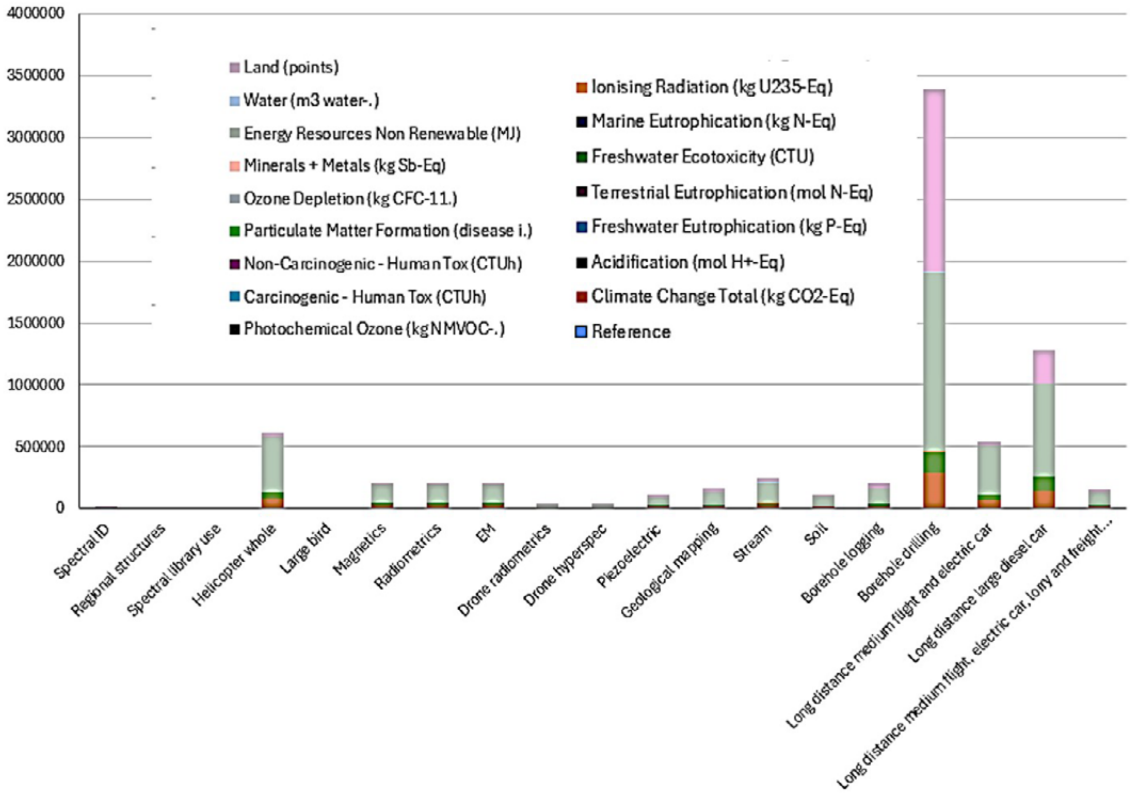

Fig. 2. LCA results for exploration techniques and travel used in Greenpeg, for a campaign scenario with all the techniques and 4 x 350 drill holes (Greenpeg 2024b).

LISTENING TO COMMUNITY VIEWS AND CONCERNS DURING EXPLORATION

Twenty-four in-depth interviews were carried out in Wicklow, Ireland and 16 in Hamarøy, Norway (Greenpeg 2024a). The focus of the analysis was perception of exploration and mining, understanding local communities, cultural priorities, context, and economic activities. Textual analysis was carried out and recurring themes, including environment, health and safety, trust in companies and authorities, sense of place and perception of risk were identified. In Ireland, the most worries were related to possible future mining. In Wicklow, there had been relatively little contact between the exploration company and the community. In the absence of other information people imagined the worst. We liken these worries to ‘monsters’ that people worry about even though they might be scenarios, e.g. salar-style mining for pegmatites, that technical experts would consider unlikely or practically impossible. These ’monsters’ cause considerable anxiety and stress. In, Hamarøy, Norway, where there is a long-established mining and processing operation, set in a predominantly Sami community, with the backdrop of historical Sami repression, the company was generally well-accepted and is a key employer. There was a desire to be included in consultations on exploration from early in the process and it is clear from all our research that this is vitality important. These relationships need depth and real attempts at understanding and cooperation. Views also expressed in Norway about connection to and the spiritual importance of nature will be familiar from multiple different indigenous cultures around the world, but this was echoed by sentiments in Ireland when discussing the value of the natural world, the environment, the importance of 'home' and 'sense of place'.

In Cornwall and Portugal, our surveys of the public followed helicopter-borne – highly visible and audible – exploration. Five hundred and eleven questionnaires were completed in Cornwall, UK and 47 in Barroso-Alvão, Portugal (Greenpeg 2024a). Both communities said they would have liked more information about the surveys. Where respondents received information prior to seeing the helicopter they were generally happier about it and more positive about exploration. Results contrasted markedly in the two areas about whether the communities felt positive or negative towards the possible return of mining. In Cornwall 59% slightly agreed/strongly agreed that mining would be good for the region, 15% disagreed, whereas in Portugal, only 32% agreed and 54% strongly disagreed with that sentiment.

COMPANY ROUTES TO PRODUCTION

Our Portugese study area was close to the controversial Barroso lithium pegmatite project, which was one of the seven projects included in our desk study of company practice (Greenpeg 2023). The concept is that projects travel along a reasonably direct route from desk studies and early-stage exploration all the way through to mine development, by deploying actions from a toolbox of good practice in community interaction and partnership. As soon as community concerns arise, then the company response will take time and energy — i.e. a longer and more time-consuming diversion towards the next stages of the project. Companies respond by using more resources from the 'toolbox of supporting actions'. Early application of roadmap supporting actions can reduce problems or at least make them easier to navigate.

RAINBOW OF RECOMMENDATIONS

We have distilled the conclusions of the LCA study and the social research into a set of practical recommendations that junior exploration companies searching for pegmatites and other critical mineral deposits can follow without great expense or extra work (Table 1). This could be used alongside other exploration guidelines. We reviewed various protocols and found the Prospectors and Developers Association of Canada Driving Responsible Exploration scheme (PDAC 2024; formerly E3plus) to be a useful and practical guide. This includes specific guidance on radioactivity which is relevant to some (NYF) pegmatites and now also has a carbon calculator.

Table 1. Practical recommendations for junior exploration companies.

Relationship build early Review plans throughout	ESG plans need to **start early** with **regular review and revision** throughout any project because the environmental, social and governance context can frequently and dramatically change, irrespective of company actions. Many communities worry about environmental impact of future mining and implications for their health and way of life, particularly at the very local scale. The growth and spread of this anxiety and fear in a community, even from an early project stage, is the main social impact of exploration that needs recognition and empathy. In the absence of other communications, people are likely to imagine the worst so **good communication** is key. **Relationship building** and community participation in projects may be key to tackling these worries, which otherwise may stall or halt the progress of a project.
Use Shared data	**Sharing a large data library** during exploration greatly decreases the environmental impact of data use, so using satellite data, spectral libraries, and airborne surveys collected for open use is low environmental impact.
Combine activities	**Combining exploration activities** within one trip or using an aerial platform for multiple types of sensors maximises the data collection potential for the same given environmental impact, thus proportionately reducing the environmental impact per technique.
Think travel	**Travel** to field areas from home / office bases, as well as travel integral to field activities between field accommodation and sites, are major contributors to the impacts of exploration. Plan carefully to find the most environmentally efficient solutions. (Also check out PDAC's DRE carbon calculator https://ghgcalculator.pdac.ca/).
Remember labs	It is important to consider **lab consumables,** e.g. Ar that may have high impact. Impacts can be greatly reducing by using zero or low carbon suppliers.
Decrease Drilling impacts	**Drilling impacts are significantly more than any of the other exploration techniques** analysed, including the application of helicopter-borne geophysics surveys and travel to site for an exploration campaign. Using drilling as effectively as possible and innovating with low-carbon drilling solutions will lower the environmental footprint.

ACKNOWLEDGEMENTS

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SOCIO-ENVIRONMENTAL ASPECTS RELATED TO THE IMPLEMENTATION OF STRATEGIC PROJECTS

by

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INTRODUCTION

The EU's Green Deal aims to increase its manufacturing capacity and support its clean tech industry and supply chains. The Critical Raw Material Act (CRMA) is the main Regulation (EU 2024/1252) for the establishment of a framework for ensuring a secure and "sustainable" supply of critical raw materials (CRMs). It includes a list of CRMs that are important for the European economy and face a high risk of supply disruption. The CRMA aims to ensure that European extraction, processing and recycling of strategic raw materials (SRMs) meet 10%, 40% and 25% of EU's demand by 2030, respectively. For example, lithium, cobalt, nickel, manganese and graphite are needed for the manufacture of batteries for e-mobility and energy storage, while rare earth elements (REEs) are required for the manufacture of motors of electric vehicles and wind turbines. The same day CRMA entered into force, the Commission published a call for submission of proposals for recognition of projects as Strategic Projects (SPs). On March 25, 2025, the Commission adopted 47 SPs (Fig. 1), for the extraction, processing, recycling or substitution of SRMs, to substantially improve its domestic capacities and strengthen the European raw materials value chain by modifying and broadening the sources of supply. These projects have cross-border benefits beyond the EU Member State concerned.

The 47 projects will be implemented in 13 Member States, namely Belgium, Czechia, Estonia, Finland, France, Germany, Greece, Italy, Portugal, Poland, Romania, Spain, and Sweden. They cover 14 of the 17 SRMs (bismuth, silicon metal and titanium metal were not covered by SPs in the first list) mentioned in the CRMA, while 25 projects involve extraction activities, 24 processing, 10 recycling and 2 substitutions of raw materials. 22 of these projects are related to lithium, 12 to nickel, 10 to cobalt, 7 to manganese and 11 to graphite, elements that are important for the EU battery raw material value chain. Also, one project involves magnesium and three involve tungsten that may contribute to the resilience of the EU's defence industry. These projects are an important milestone in the implementation of the CRMA and if initiated as planned and completed successfully will contribute to Europe's green and digital transitions, and also support several industrial sectors including aerospace, renewable energy, electronics, defence

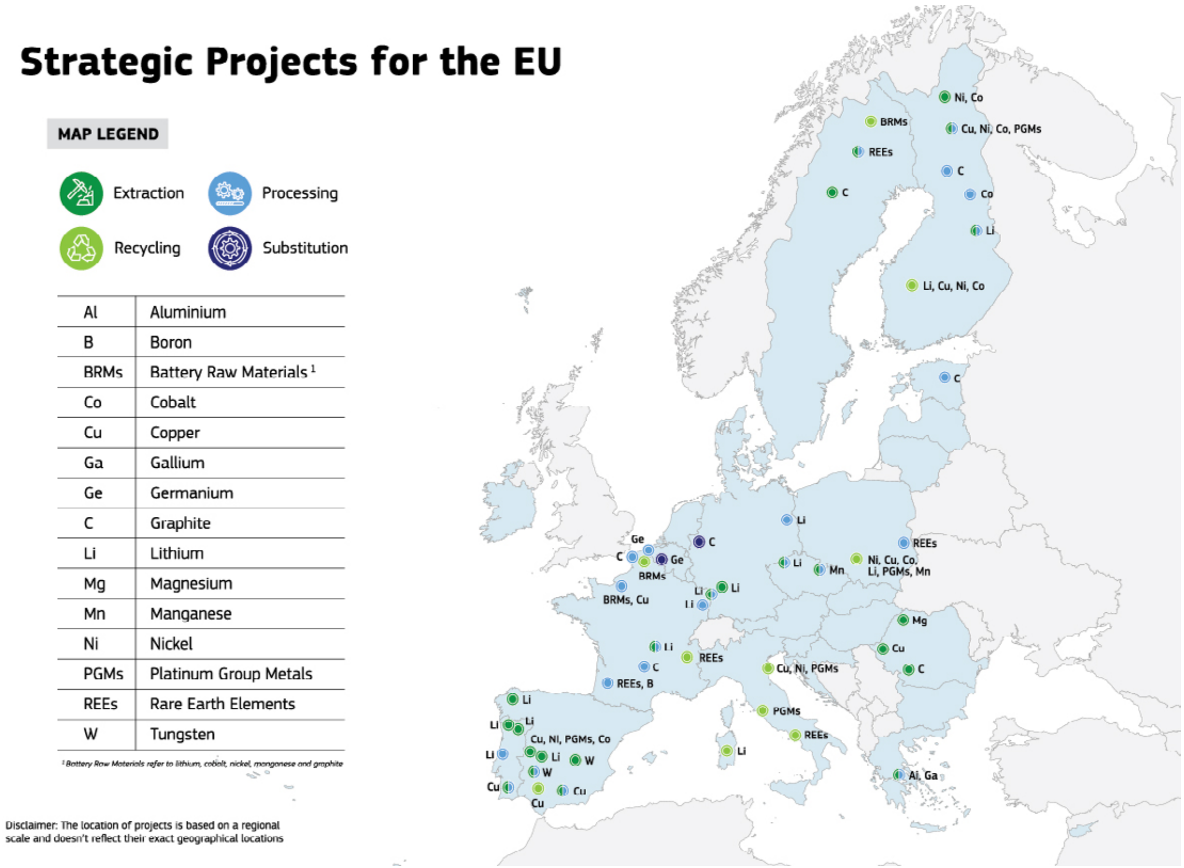

Fig. 1. Location of SPs for the extraction, processing, recycling or substitution of SRMs in the EU (https://ec.europa.eu/commission/presscorner/detail/en/ip_25_864).

and transport. The capital investment needed so that SPs become operational exceeds €22.5 billion. Their successful implementation requires the coordinated support by the Commission, Member States and financial institutions, including the European Investment Bank (EIB), the European Bank for Reconstruction and Development (EBRD), European Regional Development Fund (ERDF) / Cohesion Fund, and private financial institutions).

IMPORTANT SOCIO-ENVIRONMENTAL ASPECTS – ISSUES OF CONCERN

It is known that the Social License to Operate (SLO) / Public Acceptance (PA) is an informal social contract that emerged some 30 years ago to bridge the gap between the mining industry and the society by incorporating the principles of Global Mining Initiative (GMI) (Komnitsas 2020, Ruokonen 2020). SLO/PA will be a major challenge during the entire life cycle of the SPs and will depend on several factors of varying importance for different projects; these may include among others the type of the ore extracted / metal produced, the associated land uses, the previous practices (if any) of responsible mining, the response to mining accidents / the taking of responsibility and the rehabilitation / compensation actions planned, the level of education and quality of life in the areas of concern (involving health care, energy price, state of the environment), the trust in regional / central government and the relations among all involved stakeholders (Eerola & Komnitsas 2025).

The SPs will benefit from streamlined permitting and access to finance. The Commission confirms that for SPs in line with the CRMA, the permit-granting process will not exceed 27 months for extraction projects and 15 months for other projects. However, the acceleration of the procedures may raise concerns that may cause legal implications, public opposition and finally delays; currently, the permitting processes can last from five to 10 years. The Commission also confirms that all projects will be implemented by following all environmental, social and governance (ESG) standards, thus streamlined procedures will not imply lower standards on environmental assessment or reduced involvement of the public. Thus, all SPs will be subject to environmental assessments and public consultation requirements.

The quality of all environmental media (soil/water/air) and the conservation of nature must be non-negotiable criteria. A single case of contamination / accident may spark protests and threaten the implementation also of other SPs. The technical and financial feasibility of SPs also need to be clearly justified. To increase transparency, the SPs must maintain a regularly updated website that provides detailed information to all relevant stakeholders and mainly the local population on the projects' progress, impacts and benefits; also, their interaction with local communities must be clearly demonstrated.

Special attention needs to be paid in case projects affect minorities / indigenous people and their land or are implemented in sensitive areas or areas of specific environmental and cultural importance (UNESCO World Heritage sites, biodiversity hotspots, and (sub)arctic ecosystems). The poor sensitivity shown in some cases in the past by industry in addressing social and environmental issues has often led to violent conflicts. The lessons learned so far by all stakeholders are most probably the best guide for the development of an efficient and transparent roadmap, involving several well-established milestones that will monitor the progress made by the SPs and also safeguard the future activities which may be revised when needed. The implementation of life cycle assessment (LCA) and social LCA (S-LCA) studies to quantify greenhouse gas (GHG) emissions, energy use associated with all stages of SPs, water consumption and re-use as well as the social impact, involving human health and well-being, land use, social justice, economic stability and prosperity, is crucial for the development of trust among the industry and the involved stakeholders (Bartzas & Komnitsas 2024, Souza et al. 2025). Overall, some of the most important aspects for the successful implementation of SPs include:

- Increased transparency during the implementation phase; there are accusations that no access to documents was allowed by the public during the screening / selection stage, but this is how the evaluation process is carried out; several of the submitted documents contain confidential information and personal data that cannot be disclosed to the general public and other industries.
- Update of mining legislation pertinent to the management of waste from extractive industries (Directive 2006/21/EC amending 2004/35/EC); it is known that in several (third) countries management of wastes is carried out according to different standards (e.g., for the construction of tailing dams, the disposal of wastes, the collection, treatment and release of leachates to water reservoirs / streams). It is believed that the management of mining wastes according to the EU's Best Available Technologies (BAT 2018) will improve the prestige and image of the industry.
- Update or revision, if needed, of other related EU legislation including, the Water Framework Directive (2000/60/EC), the Birds Directive (2009/147/EC), the Habitats Directive (92/43/EEC) and the proposed Soil Monitoring and

Resilience Directive under the EU biodiversity strategy for 2030, that is part of the European Green Deal.
- Assessment of environmental and socio-environmental impacts, through LCA and S-LCA studies to define that SPs fully meet the sustainability requirements; emphasis should be given on minimization of water and energy consumption, especially in remote and sensitive areas.
- Future SPs should target the increased contribution of recycled materials to raw materials demand - end-of-life recycling input rates (EOL-RIR).
- Strategic Partnerships between the EU and third countries must comply with the highest environmental and social standards. In November 2023, the EU signed a Memorandum of Understanding (MoU) with the Government of Greenland for a strategic partnership to develop sustainable raw materials value chains, however the recent US claims over Greenland, Canada and other countries may result in geopolitical developments.

Finally, an important pending issue is the selection and implementation of SPs located in third countries, providing that they comply with the criteria set in article 6 of the CRMA. The Commission received 46 applications after the first call and the list of the selected projects will be announced at a later stage. However, special emphasis needs to be taken because some of them, as the Jadar Valley Li project in Serbia, sparked major protests and fierce opposition, also due to the fragile political situation in the country, that resulted in cease of activities more than three years ago. In this specific case, public opposition and social unrest were intensified since July 2024 when the Serbian Constitutional Court overturned a 2022 government decision that had annulled initial planning permissions. Recently a letter backed by signatures of 100,000 citizens was given to the Delegation of the EU in Serbia urging the EU not to grant strategic status to the Jadar project. This opposition is most probably one of the reasons that the EC has not yet disclosed the list of third-country SPs. The Jadar Valley Li project is critically presented in a recent documentary film (Storyrunner/SIM^2 KU Leuven 2025).

CONCLUSIONS

SPs for the extraction, processing, recycling and substitution of SRMs aim to substantially improve the capacities of EU’s industry and strengthen the European raw materials value chain. The successful completion of SPs requires SLO / PA and the highest level of transparency in all stages of their implementation. CSR as well as ESG are crucial aspects for all interested stakeholders. Also, the set-up of an accurate risk management plan will identify early-stage potential risks and assist in the implementation of well-established and efficient remediation measures. The establishment and independent monitoring of quantitative, where possible, technological, economic, environmental and social Key Performance Indicators (KPIs), will be crucial for the development of trust between the industry and all interested stakeholders as well as the timely completion of SPs. The results of LCAs and S-LCAs will also contribute to this direction. This approach will answer to a certain degree the accusations made by NGOs and other environmental groups that CRMA is largely based on extractivism, exacerbates the depletion of mineral resources and therefore results in severe environmental impacts and deterioration of the quality of life in affected areas and for future generations.

Projects selected in this call as well as future SPs should focus on recycling and increased life cycle of (electronic) components and equipment to reduce the need for the extraction of CRMs as much as possible. The EU may also set benchmarks for the next 10-20 years, for efficient use of resources, responsible mining, valorisation of wastes for the production of high added-value materials, minimization of environmental impacts as well as efficient communication between the policy makers, the industry and all involved stakeholders in the raw materials sector.

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DEEP EXPLORATION BOOSTED BY ADVANCED EXPLORATION TECHNOLOGIES – DEEPBEAT

by

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The discovery of deep deposits by surface methods is challenged by the distance from the surface to the mineralisation as a source of a geochemical signal. DeepBEAT is a Horizon Europe-funded project to advance geochemical methods for the identification of deep-seated mineral deposits, propelling Europe to the forefront of scientific innovation in the field. The aim of the project is to develop interdisciplinary, holistic, and sustainable exploration approach that combines deep geochemical knowledge to geophysics and social aspects. DeepBEAT will provide tools to comprehensively map available resources, facilitating informed planning for sustainable exploration and production practices aligned with the goals of responsible resource management. Recognising the crucial role of public support, DeepBEAT is dedicated to promoting awareness, aiming to engage scientists, exploration and mining companies, and stakeholders in meaningful interactions with the public.

The final outcome DeepBEAT will be a workflow which addresses these aspects by two means: I) DeepBEAT plans to engage with the local communities at the test sites to learn about concerns, hesitancy and what is the emotional core of these. Experiences from these events will be included in exploration workflow as an integral part, following the principles of free, prior, informed consent, which requires to interact with communities at a very early stage. II) DeepBEAT proposes ten novel technological developments, all designed to minimise impact on environment and maximise sustainability. These research and innovation developments have the potential to push the limits of surface geochemical exploration to another level.

They comprise a) new insights to ultra-high resolution analytical chemistry, b) increasing sampling strategy efficiency, c) introducing groundbreaking new concepts of dealing with elemental measurement data, d) reducing exploration costs by sample selection, e) testing novel phyto-geochemical media, and f) introducing UAV assisted biogeochemical sampling. Detailed understanding of the deposits complements the workflow to allow the understanding of the mineralization as part of mineral systems and AI-assisted 3D mineral prospectivity modelling.

The DeepBEAT project (2024–2027) is coordinated by Helmholtz-Zentrum DresdenRossendorf. The project consortium consists of eight partners and five associated partners from Germany, Finland, France, the Czech Republic, and Canada. Three test sites with varying deposit styles were chosen to conduct the research: Volcanic massive sulphide mineralisation system at Saramäki, Finland, granite-porphyry related Li-Sn-W deposits at Erzgebirge-Krušné hory area, Germany, and alkaline metasomatite REE-Zr-Mo mineral system at Hůrky, the Czech Republic. The progress of the project can be followed on the project webpage at www.deepbeat.eu, and in LinkedIn, X (Twitter) and Instagram. DeepBEAT is funded by the European Union under the GA number 101177617.

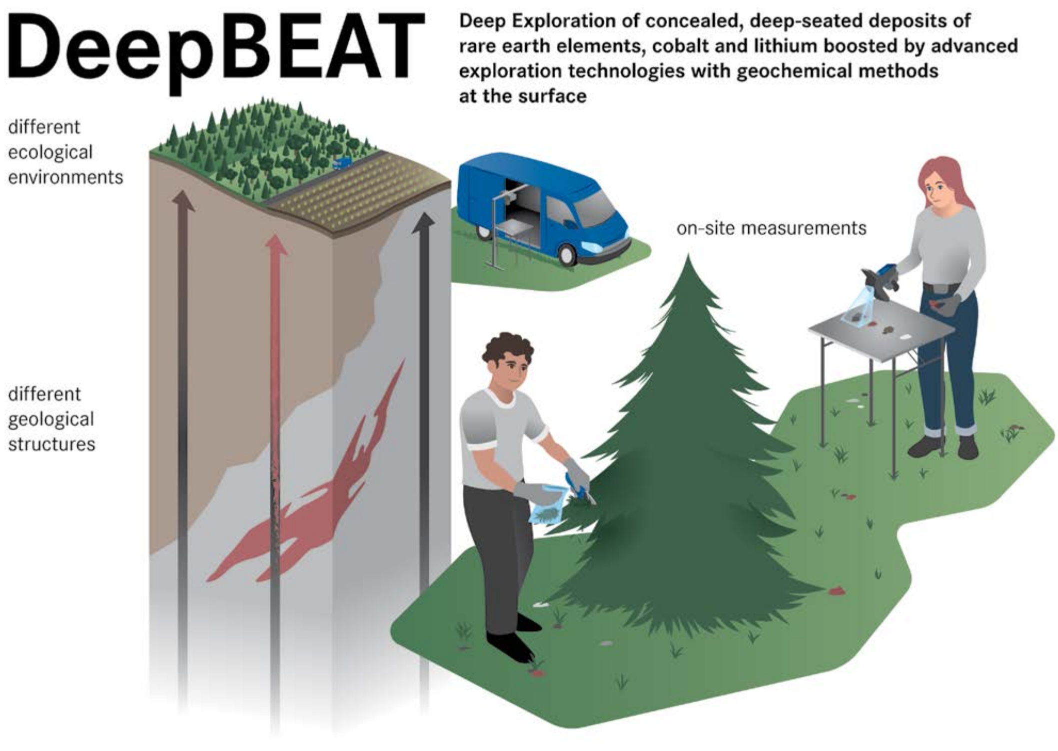

Fig 1. DeepBEAT samples plants, treetops, resin, mushrooms, soil, stream sediment or altered rock samples which capture a geochemical signal from deep sources. Portable tools like X-Ray Fluorescence (XRF) and Laser Induced Breakdown Spectroscopy (LIBS) enable rapid, on-site mineral analysis, while Triple Quadrupole Inductively Coupled Plasma Mass Spectrometry (TQ-ICP-MS) supply high-resolution data on the elements. UAV and LIDAR-assisted sampling design and sampling protocols streamline data collection of tree canopies. Furthermore, AI-driven 3D modelling reveals deeply buried or hidden deposits.

ENHANCING MINERAL SYSTEM MODELLING AND PROSPECTIVITY MAPPING WITH OPEN-SOURCE TECHNOLOGIES: INSIGHTS FROM THE EIS HORIZON EUROPE PROJECT

by

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INTRODUCTION

The Exploration Information System (EIS) is an initiative focused on advancing mineral systems modelling and mineral prospectivity mapping through open-source tools (EIS 2025). This project is a collaboration among 18 partners across six EU member states (Finland, France, Germany, Spain, the Czech Republic and Sweden) and beyond (South Africa and Brazil), integrating expertise from academia, research institutes, industry, and service providers. The EIS project is funded by the European Union's Horizon 2020 Europe research and innovation program under grant agreement no. 1010557357.

PROJECT OBJECTIVES

EIS addresses the EU's need for critical raw materials (CRMs) by developing innovative data analysis and modelling tools. Central to the project are the ***"EIS Toolkit"*** and ***"EIS QGIS Wizard"***, open-source tools build on QGIS platform designed to enhance exploration efficiency, reduce environmental footprints, and strengthen sustainable resource management. These tools leverage advanced methodologies, including machine learning and artificial intelligence, to refine mineral prospectivity analysis and predictive mapping across diverse mineral systems, such as VMS (Volcanogenic Massive Sulphide), granite-related lithium-tin-tantalum-tungsten, and IOCG (Iron Oxide Copper-Gold).

Fig. 1. EIS objectives.

METHODOLOGY

The EIS project promotes a hybrid approach that utilizes mineral systems modelling as the foundation for mineral prospectivity modelling. A crucial component of the EIS is a library of geological fingerprints representing diverse types of mineral systems. These fingerprints are used to identify the most relevant mappable geoscientific features essential for successful prospectivity analysis. The project focuses on three mineral systems as case studies:

1. Cobalt minerals in volcanogenic massive sulphide (VMS) systems
2. Lithium-tin-tantalum-tungsten minerals in granite/pegmatite-related systems
3. Rare earths-cobalt minerals in iron oxide copper-gold (IOCG) systems

Selected mineral deposits within the partner countries of the EU serve as study or test sites. Additionally, reference sites in South Africa and Brazil, specifically the Li-bearing pegmatite in the Orange River Pegmatite Belt and the Carajás IOCG province, provide further insights.

Geo-models and mineral systems modelling are being integrated into mineral prospectivity mapping in the EIS project context. This integration allows for a more comprehensive understanding of mineral systems and enhances the accuracy of prospectivity analysis. By combining geological knowledge with advanced data analysis techniques, the EIS project aims to provide a robust framework for mineral exploration.

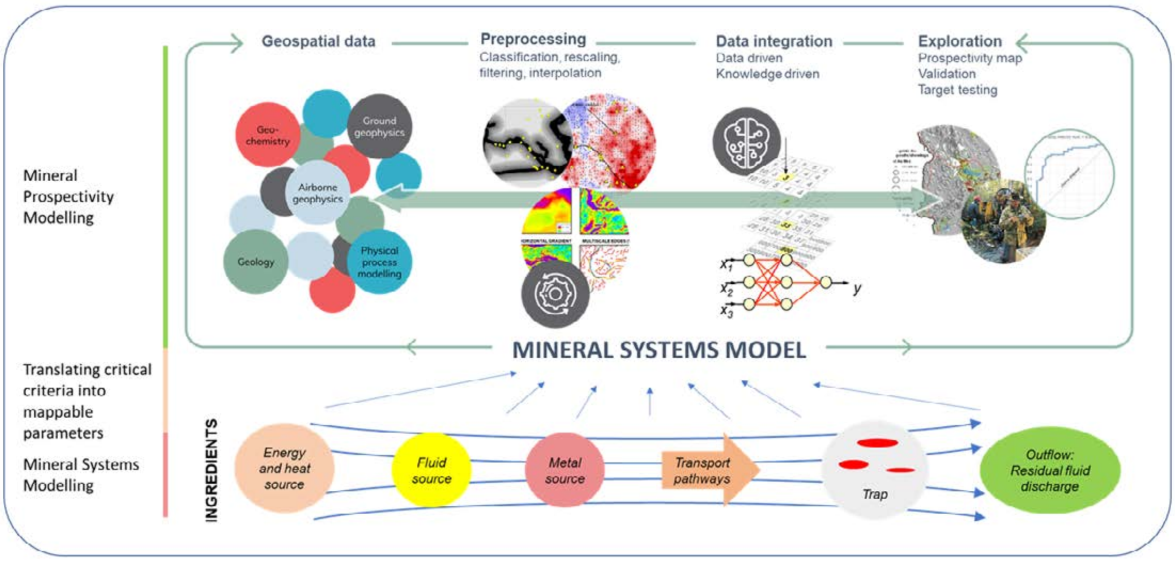

Fig. 2. Mineral systems approach combined with mineral prospectivity mapping in EIS.

EIS TOOLKIT

The presentation will showcase the newly developed "EIS Toolkit", which, as a backbone of the entire "EIS QGIS Plugin", includes preprocessing tools, validation tools, and new data analysis methods by incorporating AI with machine learning and deep learning. These tools are designed to streamline the process of mineral prospectivity analysis, making it more efficient and accurate. "EIS Toolkit" is freely available from GitHub (Gispo 2025a).

EIS QGIS PLUGIN

The first beta release of the open source "EIS QGIS Plugin" consists of a collection of software tools for semi-automated exploration targeting in Quantum QGIS. This plugin is designed to facilitate the integration of exploration data and geological models into GIS platforms, making it easier for researchers and explorers to identify potential mineral deposits. "EIS QGIS Plugin" is freely available from GitHub (Gispo 2025b).

CASE STUDIES

The EIS project focuses on three mineral systems as case studies:

1. **Cobalt minerals in volcanogenic massive sulphide (VMS) systems:** These systems are characterised by the presence of cobalt minerals within sulphide deposits formed by volcanic activity. The project aims to develop models that can predict the occurrence of these minerals based on geological and geochemical data.
2. **Lithium-tin-tantalum-tungsten minerals in granite/pegmatite-related systems:** Granite and pegmatite-related systems are known for their rich deposits of lithium, tin, tantalum, and tungsten. The EIS project utilises advanced modelling techniques to identify potential areas for exploration and extraction of these critical minerals.
3. **Rare earths-cobalt minerals in iron oxide copper-gold (IOCG) systems:** IOCG systems are significant sources of rare earth elements and cobalt. The project aims to enhance the understanding of these systems and develop predictive models for mineral prospectivity.

Overall, the EIS project is developing more than 12 case studies addressing these mineral systems, covering various scales, from camp to national, and various geodynamic domains, across Europe and beyond (Fig. 3). These case studies not only test the toolkit and QGIS plugin developed by the project, but they also use them to develop and benchmark prospectivity models using diverse methods. These test case studies demonstrate the capacity and benefit of combining expertise of economic geologists with modern machine learning algorithms to further increase the accuracy and reliability of mineral prospectivity mapping.

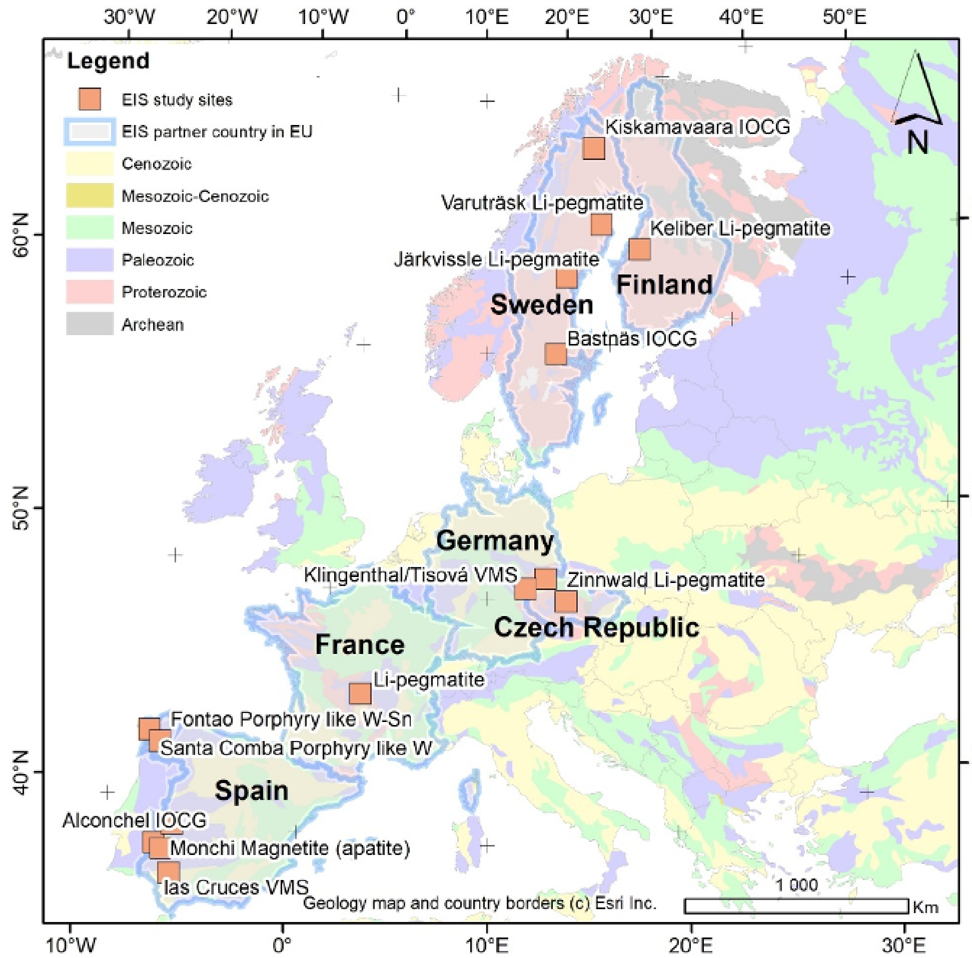

Fig. 3. EIS test sites across Europe. In addition, the project has test sites in South Africa and Brazil.

CONTRIBUTIONS TO THE EU’S CRIT

ICAL RAW MATERIALS ACT GOALSThe EIS project contributes to the EU’s Critical Raw Materials Act goals by emphasizing cross-sector collaboration and open-access innovation. By aligning research, industry, and societal goals, EIS demonstrates how EU-funded projects can foster sustainability, economic resilience, and resource efficiency in the raw materials sector. The project’s innovative tools and methodologies aim to enhance exploration efficiency, reduce environmental footprints, and strengthen sustainable resource management.

CONCLUSION

The EIS project represents a significant advancement in mineral exploration within the EU. By leveraging open-source technologies and integrating AI and machine learning algorithms, the project aims to enhance the efficiency and accuracy of mineral prospectivity analysis. The insights gained from this project will contribute to the discovery of new mineral deposits and improve access to critical raw materials in Europe.

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MULTIMINER – INNOVATIVE EARTH OBSERVATION METHODS FOR MINERAL EXPLORATION AND MINE SITE MONITORING

by

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The European Union aims to become a carbon-neutral economy by 2050, necessitating an industry transformation in the raw materials sector to ensure a sustainable supply of critical (CRM) and strategic (SRM) raw materials. The EU Action Plan for CRM 2020 and the CRM Act of 2023 outline specific actions to mitigate supply risks, protect the environment, and secure the EU's strategic autonomy in the raw materials market. These initiatives, along with the European Green Deal, the Circular Economy Action Plan and several international, and state level regulations, emphasise the integration of sustainability and circularity principles across the sector.

The Horizon Europe funded Research and Innovation Action project "Multi-source and Multi-scale Earth observation and Novel Machine Learning Methods for Mineral Exploration and Mine Site Monitoring" (**MultiMiner**, 2023–2026, Grant number 101091374) aims to enhance the efficiency of mineral exploration and mine site monitoring through the development of innovative, highly automated data processing algorithms (Fig. 1). These solutions leverage Earth Observation (EO) technologies and novel machine learning methods, requiring minimal *in situ* reference data. MultiMiner's EO-based exploration solutions have very low environmental impact. They improve safety and are environmentally safe, making them potentially more socially acceptable than traditional CRM exploration methods. MultiMiner's solutions for mine site monitoring increase the transparency of mining operations by offering new and innovative tools for the detection of environmental impacts.

The project demonstrates the applicability of its algorithms through case studies at five European test sites (Hochfilzen, Austria; Ihalainen, Finland; Kallyntiri, Chalkidiki and Kirki; Greece), utilizing data from sources like Copernicus Sentinel-1 and Sentinel-2, EnMAP, and drone-borne hyperspectral, radiometric and multi-band SAR sensors. These case studies validate the effectiveness of MultiMiner's solutions in real-world mining and exploration environments, ultimately contributing to the EU's autonomy in raw materials and promoting environmentally sustainable mining practices.

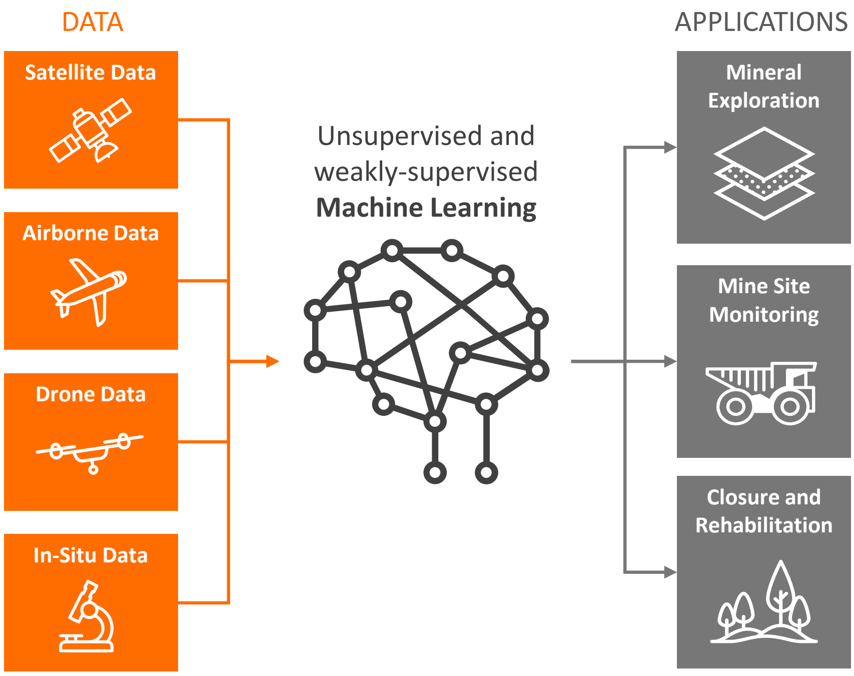

Fig. 1. The MultiMiner project focuses on developing EO data using unsupervised and weakly supervised Machine Learning approaches for a wide range of applications in mineral exploration and mine site monitoring.

The MultiMiner project focuses on creating robust, scalable, and transferable tools for mineral exploration, utilizing multi-source EO data across various scales and platforms (drone, airborne, spaceborne). The developed algorithms are designed to improve the accuracy and time-efficiency of mineral identification of CRMs and SRMs based on EO data. Key developments of the project, which are described in the following paragraphs, include a Mineral Mapping Algorithm, workflows for multi-scale EO data interpretation, a Mineral Prospectivity Wizard and a Generic Mine Site Monitoring algorithm.

The Mineral Mapping Algorithm (MMA) is developed for automatic spectral feature extraction from a comprehensive mineral spectral library. Hyperspectral data were acquired using SPECIM AISA Fenix system mounted on a tripod to perform terrestrial mine wall scans. The wavelength coverage is from 400 to 2500 nm and the spatial resolution of about 30 cm per pixel. Reflectance retrieval was carried out using a 95% diffuse reflecting white reference. Figure 2 shows results from *in situ* data analysis applying the spectral feature fit method by comparing mineral diagnostic spectral feature from a reference sample taken from the spectral library with the unknown pixel spectrum. The distribution shows best fit in red and low fit in dark blue colors.

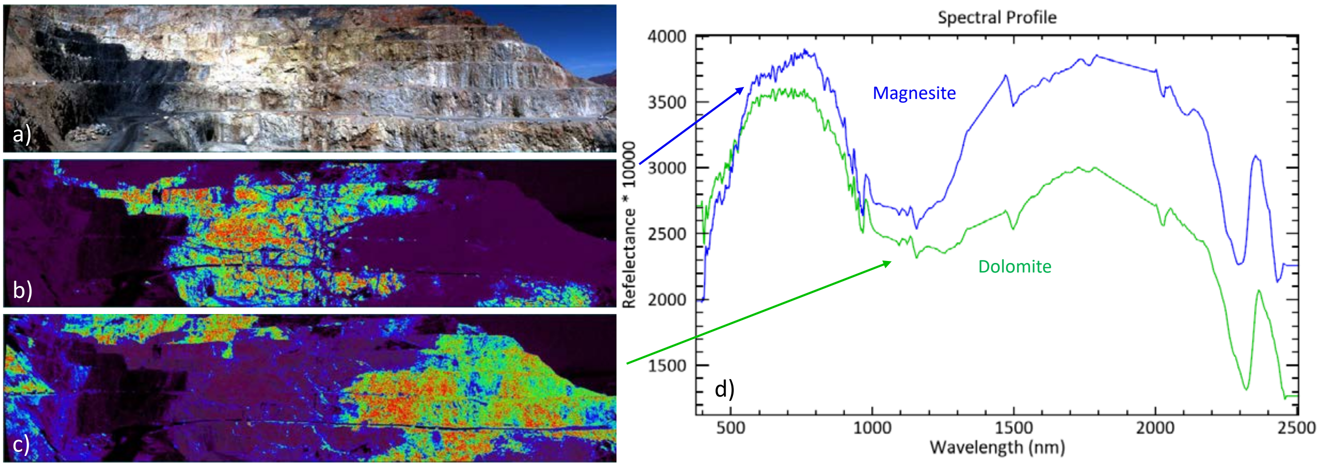

Fig. 2. Detailed mining wall scanning for mineral mapping: a) Open pit, NE wall, 30th July 2024, AISA Fenix, True colour image. b) Open pit 30th July 2024, AISA Fenix, magnesite abundances. c) Open pit 30th July 2024, AISA Fenix, dolomite abundances. d) Spectral profiles of magnesite and dolomite.

Workflows for multi-scale EO data interpretation are implemented to add value to data analyses by integrating various data types. The workflows are operated through a guided **Mineral Prospectivity Wizard (MPW).** The open access demonstrator is a GUI-based step-by-step assistant (Fig. 3) that guides users through various data processing and analysis steps, including pre-selection of minerals from the spectral database, displaying, processing and classifying different remote sensing image data (hyperspectral, multispectral, RGB, etc.), and defining the analysis methods, output products (e.g., mineral distribution maps, proxy maps, etc.), and machine learning algorithms. The tool harmonises the data spectrally and spatially to enable consistent and reproducible analyses. By using the GUI, the user can process the remote sensing data in one well-structured workflow to generate the desired remote sensing products related to mineral exploration purposes.

In addition to exploration, MultiMiner develops EO solutions for mine site monitoring throughout the entire mining lifecycle, including 1) 3D/4D monitoring of composition and volume of tailings storage facilities, 2) automatic interpretation of European Ground Motion Service products, producing maps for dam stability and open pit stability, 3) algorithms and maps of ground moisture, supporting dam stability as well, 4) monitoring algorithms for water quality and acid mine drainage, 5) algorithms and maps of revegetation status, including vegetation structure and plant diversity and 6) multi-source models for atmospheric and surface dust monitoring. Encompassing most of these thematic applications, an ambitious **Generic Mine Site Monitoring algorithm (GMSM)** is developed. GMSM performs these monitoring tasks with advanced deep learning methods, combining EO foundation models with trainable adaptive decoders, making use of the vast amounts of available EO data and sparser in situ data (Fig. 4).

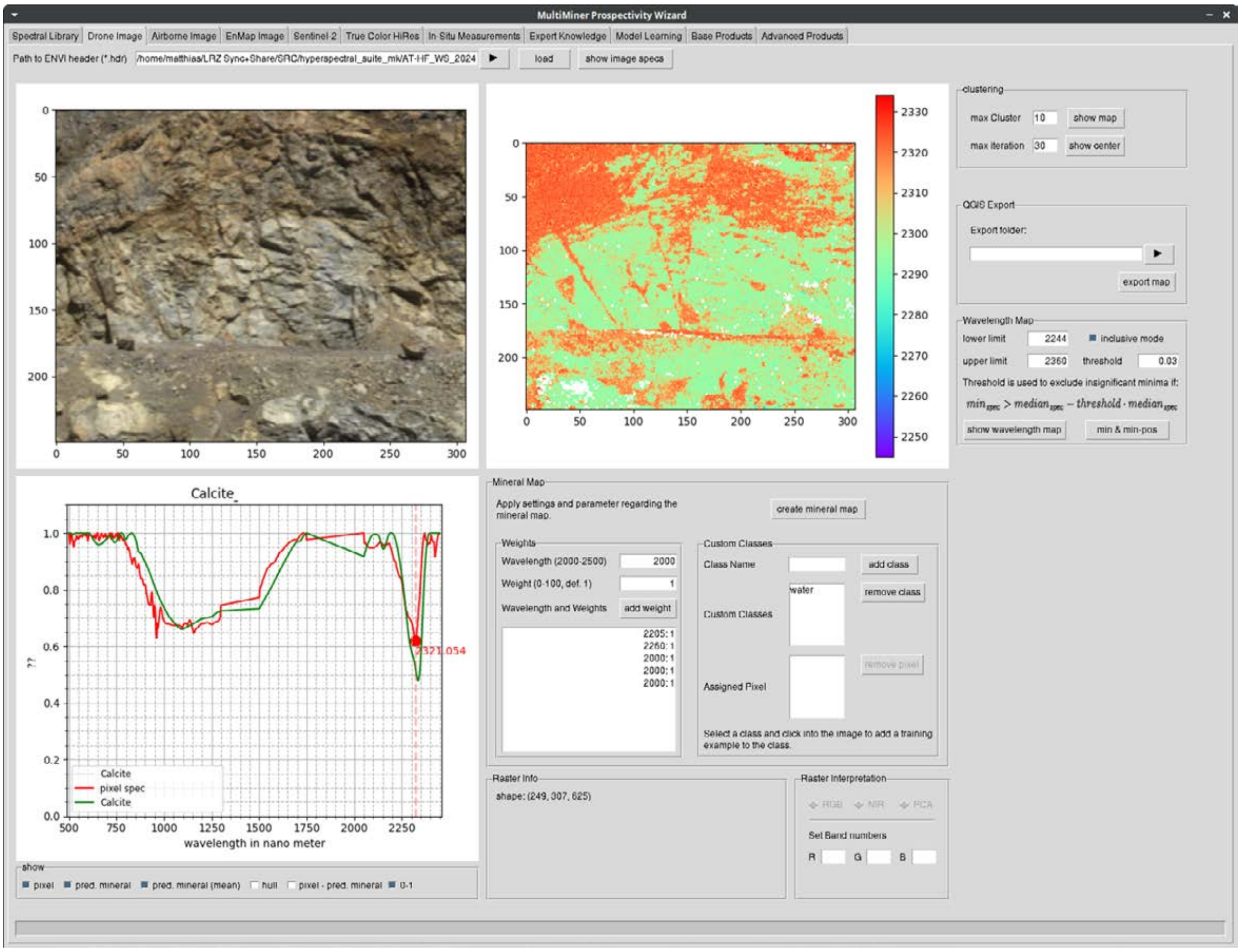

Fig. 3. The preliminary interface of the MultiMiner Mineral Prospectivity Wizard (MPW) shows how the data are handled as well as the first results. The map on the right side shows the wavelength position of the carbonate feature. Red colors indicate dolomite and the green magnesite.

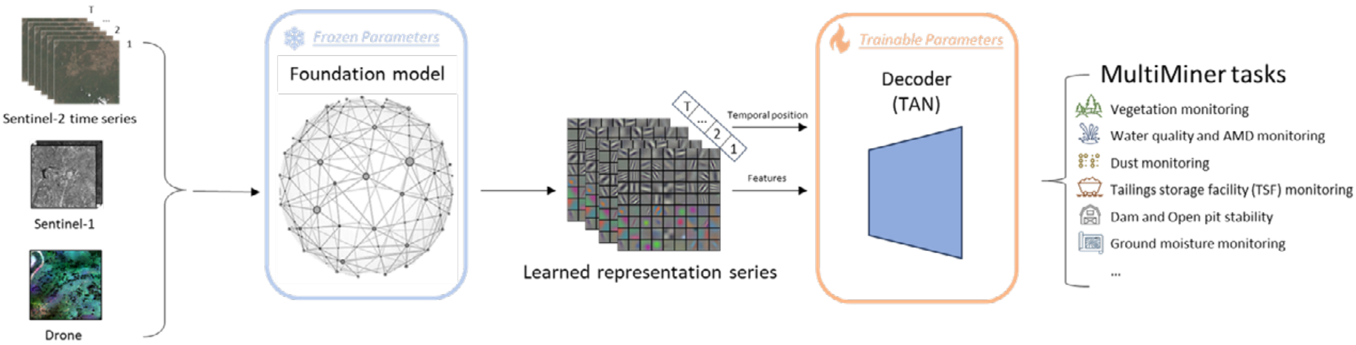

Fig. 4. GMSM for multimodal inputs and different downstream tasks. The foundation model was pretrained using vast amounts of multi-sensory EO data. The Decoder is a Temporal Attention Network (TAN), which embeds the temporal information of the input data, together with the features representation from the foundation model.

MultiMiner's developments and results will be showcased in detail at a conference to be organised towards the end of the project. The generated tools will also be available for further exploitation and development through Github.

ADVANCING DEEP-LAND EXPLORATION TECHNOLOGIES AND SOCIAL ACCEPTANCE STRATEGIES IN THE DEXPLORE PROJECT

by

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INTRODUCTION

The transition to a climate-neutral and digitised economy demands a significant increase in the supply of Critical and Strategic Raw Materials (CRM and SRM) (IEA 2021, Kim et al. 2021). However, with the European Union’s domestic production covering less than 3% of the required CRM and SRM, there is a pressing need to develop advanced exploration technologies for boosting the domestic supply as stated by the Critical Raw Materials Act (European Commission 2024).

Moreover, public awareness and acceptance are crucial for the successful implementation of sustainable resource extraction projects. Social sciences play a central role in addressing environmental and social concerns associated with mining activities. Engaging communities through participation processes and conflict resolution approaches can help establish global standards for more socially just extraction of raw materials.

DEXPLORE HOLISTIC DEEP-LAND EXPLORATION PACKAGE

DEXPLORE is a deep-land exploration European project funded with 4.7M€ under the Horizon Europe Cluster 4. Officially starting on the 1st of October of 2024, the project will be active for 36 months.

DEXPORE mission is to contribute to addressing the European challenges regarding the CRM supply by combining cutting-edge technologies at different levels starting at the Earth surface and reaching at least 600 m depth – advanced geochemistry, EO and optical techniques, geophysical exploration including airborne and land-based surveys, together with visualisation tools of innovative approaches such as Extended and Augmented Reality required to efficiently develop accurate new ore models for deep-seated CRM/SRM while deploying innovative social acceptance strategies (Fig. 1).

Three pilot zones—fluorite mineralisation in northern Spain, VHMS deposits of the Iberian Pyrite Belt, and sulfide-bearing gneisses of Estonia—will serve as testbeds for these technologies.

Thus, DEXPLORE will propose mineral models for geological terrains well extended across Europe, such as crystalline and metamorphic rocks, and disseminated mineralisation or along planar structures, targeting CRM and SRM at least up to 600 m depth: Fluorite (Fluorspar – CRM), Copper (SRM), Nickel (SRM), Manganese (SRM and CRM), Natural Graphite (CRM) as well as Zinc (Zn), Lead (Pb), and Molybdenum (Mo).

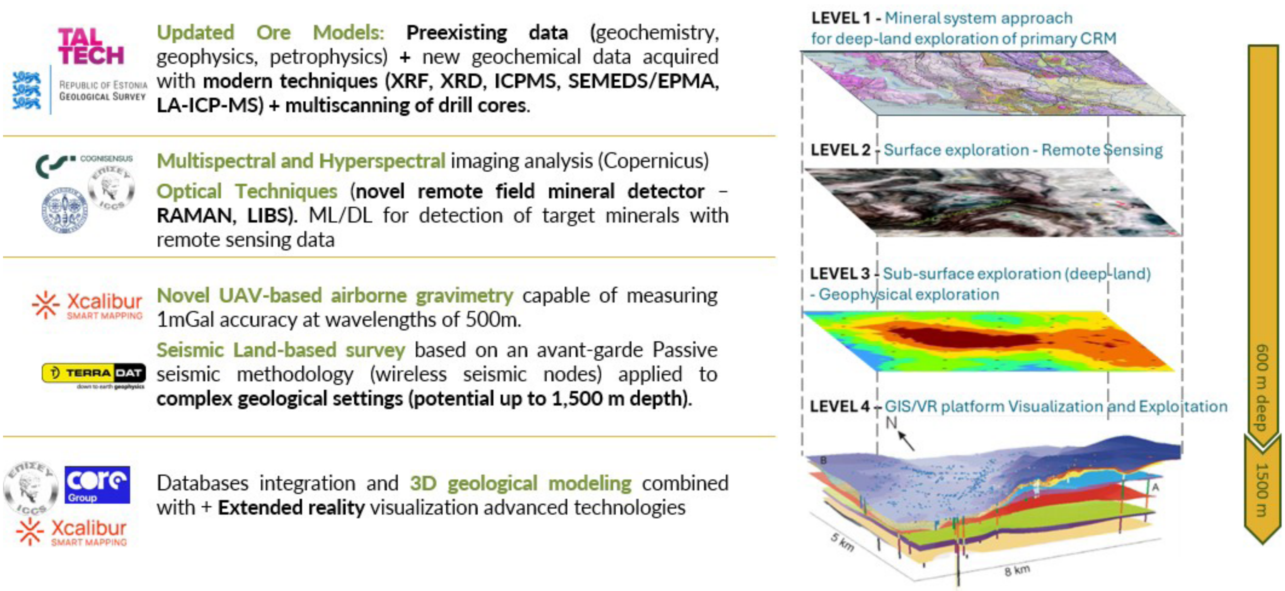

Fig. 1. DEXPLORE complete innovation package from surface to subsurface.

By integrating state-of-the-art exploration technologies with robust social engagement strategies, DEXPLORE seeks to boost European discovery and extraction of CRM and SRM. This multidisciplinary effort, involving 13 partners across Spain, Greece, Estonia, and Italy, will contribute to resource security, environmental sustainability, and public trust in mineral exploration practices.

SOCIAL LICENSE TO OPERATE AS PART OF DEXPLORE

With the aim of advancing towards societal acceptance and transparency around mineral exploration and exploitations projects, DEXPLORE incorporates Social License to Operate (SLO) activities.

The project will implement educational and engagement initiatives targeting the general public and key stakeholders, including geological surveys and regulatory authorities. The Estonian model and Spanish pilot sites will serve as focal points for knowledge dissemination and community involvement.

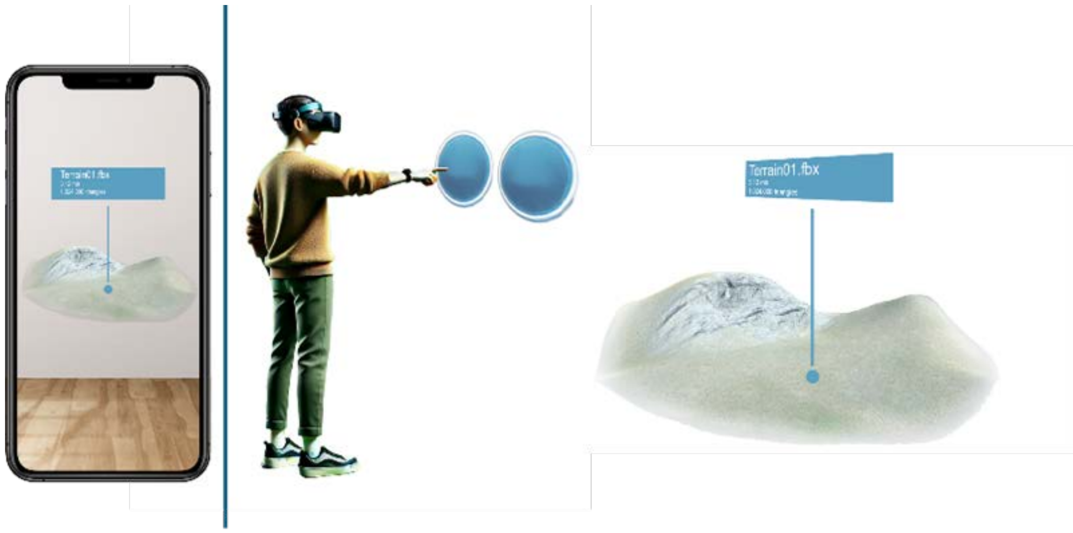

Fig. 2. Augmented Reality and Mixed Reality applications that will be part of the social acceptance strategy of DEXPLORE.

A key component of this effort is the validation of an Extended Reality (XR) platform consisting of immersive applications and a Content Management System, designed to enhance public understanding of mineral exploration. The applications enable immersive visualizations of 3D geological models, providing users with an interactive medium to explore complex geological processes (Fig. 2).

To validate its educational impact, usability testing will be conducted with diverse audiences, assessing comprehension, engagement levels, and the ability to convey responsible raw material sourcing. This validation process will include pilot testing in controlled environments before public deployment, ensuring seamless user experience and accuracy in geological data representation.

A key aspect of validation involves the application of a design thinking approach, enabling an iterative co-creation process with end-users and stakeholders while designing the XR material (Fig. 3).

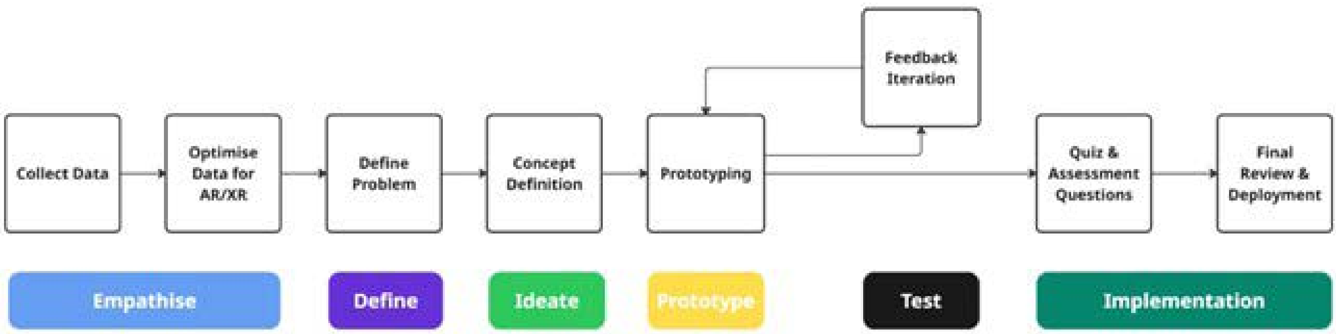

Fig. 3. The 6 Stages in the Design Thinking Process for the development of the XR content.

By integrating continuous feedback loops through structured workshops, surveys, and interactive sessions such as for instance open pilot days, the platform will evolve to reflect the needs, expectations, and concerns of its diverse audiences ensuring an inclusive approach to mineral exploration activities. This participatory approach ensures that educational content is not only scientifically accurate but also relatable and accessible, helping to dispel common misconceptions about mineral exploration.

Through iterative prototyping and testing, the platform's interactive features—including gamification elements and AI-driven content personalisation—will be refined to maximise user engagement and learning outcomes. These advanced functionalities will actively involve users, fostering a deeper understanding of the critical role that Critical Raw Materials (CRMs) play in the green transition.

By personalizing the learning journey and offering responsive, engaging content, the platform will serve as a powerful tool to raise awareness and build informed public support for sustainable mineral exploration.

By bridging the gap between industry stakeholders and communities, this initiative will enhance trust, promote informed decision-making, and ensure that exploration activities align with societal expectations and environmental responsibility.

CASE STUDY

The Estonian case study serves as a cornerstone in understanding the critical raw material (CRM) potential of the Precambrian basement within the Fennoscandian Shield (Solano-Acosta et al. 2025). By integrating advanced geophysical techniques, hyperspectral analysis, and comprehensive geochemical datasets, the DEXPLORE project targets deep-seated CRM and strategic raw material deposits in key zones such as Alutaguse, Jõhvi, and Tallinn. This effort not only enhances mineral system models but also contributes to a broader European comparison, positioning Estonia as a pivotal reference for sustainable exploration and evidence-based resource mapping.

From the Estonian partners, TalTech and the Estonian Geological Survey, data from drill cores have been provided from the Estonia's Precambrian basement. These drill cores are under the scanning process using an advanced multisensory platform, capturing high-resolution chemical, mineralogical, spectral, and physical data.

The preliminary analysis identified over 180 mineralized intervals and eight key elemental associations (e.g., Ni-Co-Cr, Ti-V-Fe, Cu-Ni-PGE) linked to critical raw materials like cobalt, vanadium, and rare earth elements. These datasets, which include quantified geochemical profiles, light absorption spectra, magnetic properties, and drill core imagery, provide a scientifically rich foundation for immersive XR experiences that communicate the geological processes, exploration techniques, and resource potential hidden deep beneath Estonia's surface.

Based on the data above, the curation of the XR campaign will follow a structured, collaborative process to ensure scientific accuracy, public relevance, and engaging delivery.

It will begin with brainstorming sessions involving technical partners, geoscientists, and communication experts to align on core messages and storytelling strategies. The next step involves a thorough assessment of the available geochemical, spectral, and visual data to identify the most compelling content and correlate it with citizen knowledge gaps identified through stakeholder input. From there, key geological concepts will be translated into immersive 3D environments and AR/VR interactions. These visuals will be accompanied by layered textual information, ensuring accessibility for a broad audience and enabling users to explore both the scientific and societal dimensions of mineral exploration in Estonia.

The XR campaign is set to launch in summer 2025 through a mobile AR app, with a version for head-mounted displays rolling out in early fall. More than just a way to learn about geology, the campaign invites users to share their thoughts and reactions as they explore—making it a space for conversation, not just information. By listening to what people find interesting, confusing, or important, the project hopes to help researchers and policymakers better understand how to talk about critical raw materials in a way that truly connects with the public.

ACKNOWLEDGEMENTS

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SUSTAINABLE EXPLORATION FOR ORTHOMAGMATIC ORE DEPOSITS, PROGRESS OF THE HEU SEMACRET PROJECT

by

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The SEMACRET project aims to develop socially and environmentally responsible exploration methods for green transition (Critical) Raw Materials (PGE, Co, V, Ti, Ni, Cu, Cr) hosted by ultramafic-mafic orthomagmatic mineral systems. The primary focus is on refining ore deposit models following the mineral systems approach, optimising regional-scale exploration targeting, and developing efficient local scale exploration methods. There are 4 reference sites serving as case studies for testing these methodologies, including Lapland in Finland, the Beja area in Portugal, the Ransko area in the Czech Republic, and the Suwalki and Sleza areas in Poland.

The project has refined multiple geochemical proxies to identify the key source (mantle) component and degree of melting for generating metal rich magmas, in both rift and orogenic belts settings. Using computational modelling, magma transportation on a whole-crustal scale and within the upper crust have been modelled. High temperature experimental studies and thermodynamic modelling have been applied to constrain the metal precipitation mechanisms. All these provide fundamental clues for guiding mineral exploration in both regional and local-scale exploration.

Regional exploration targeting for orthomagmatic mineral deposits involves the compilation of mineral system models for Ni-Cu-rich conduit-type, PGE-Cr-V-rich layered mafic intrusion systems, massif type anorthosite hosted V-Ti deposits, supplemented by the insights gained from geological modelling. We applied deep penetration geodata as predictor proxy in the modelling. These predictor maps are then integrated using a knowledge-driven approach for prospectivity modelling. The implication for future upscaling is to build up a GIS-based deep penetration geophysical database across Europe from dispersed sources, as part of the European Geological Data Infrastructure, to facilitate the utilisation of these data for guiding mineral exploration. In addition, an innovative outliner detection method has been developed which can be applied for identifying occurrence of mineral deposits.

Local-scale exploration focuses on creating an integrated solution that combines innovative methods to identify high potential areas at the deposit scale to be applied in brownfield exploration. The project developed innovative geophysical inversion methods. These include 3D inversion for electromagnetic (EM) data of sulphide ores taking into account induced polarisation (IP), and joint inversion of

EM and ground IP data. A QGIS plug-in has been developed for these modelling to integrate data processing, inversion and visualization in one single tool and is available as a user-friendly, open source and free tool. Passive seismic is widely applied for imaging deep structures on the scale of 100s of kilometres. A new processing algorithm has been developed for imaging structures at shallow depth of crust (a few km level), which has potential for imaging deep mineral deposits (e.g., 500m to 2 km). In addition, advanced modelling algorithms of full tensor magnetic gradiometry (FTMG) data has been developed. Novel environmentally friendly surficial geochemistry tools based on upper soil horizons and plant geochemistry have been explored. Moreover, machine learning-based resource modelling and 3D prospectivity modelling are under development. Many of these technologies have potential for future upscaling. Different technologies can be integrated and combined with litho-geochemical modelling, for an optimised solution for the best practice on different mineralisation styles.

Sustainable mineral exploration needs to promote social awareness on the significance of raw materials. In SEMACRET, social community events, interview and machine learning-based social media analyses have been carried out to understand the attitudes towards exploration and mining from different stakeholders. Mineral source data on key raw materials hosted in orthomagmatic mineral systems have been collected across Europe, in line with UNFC code.

AVANTIS – SUSTAINABLE, DECARBONISED VANADIUM, TITANIUM AND IRON EXTRACTION FROM EUROPE'S LOW-GRADE VANADIUM-BEARING TITANOMAGNETITE DEPOSITS

by

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INTRODUCTION

The European Commission´s Critical Raw Materials Act (CRMA) sets multiple benchmarks for reducing Europe's dependency on a few third countries for strategic/critical raw materials. Vanadium (V) and titanium (Ti) have received less attention than other CRMs such as the battery raw materials, or the light/heavy rare-earth elements that have been central to many previously funded projects. However, the situation for vanadium and titanium is no different to that of the popular CRMs: there is no domestic vanadium or (refined) titanium metal production in the EU, making the EU critically dependent on imports.

The EU is 100% import reliant for Ti metal, with a strong dependency on China and Russia. For V, this import reliance could not be calculated by the European Commission, although it is clearly also very high as once more, China and Russia are the dominant players. There is no primary vanadium extraction in the EU at present, although there are plans in Finland to recover V from steelmaking slags from 2026. It is estimated that for 2016–2021 the EU imported 1.5 Mt/y titanium (including TiO_2 pigment, Ti metal) and 12.7 kt/y vanadium. The good news is that, based on known domestic resources, the EU can supply its growing needs for V and Ti.

At present the only large-scale primary extraction of Ti-bearing minerals in geographical Europe is happening in Rogaland province in Norway, where AVANTIS partner Titania AS operates the Tellnes mine, a high-grade ilmenite mine of the magmatic type (grading 18 wt% TiO_2, as present in ilmenite, $FeTiO_3$) (USGS 2017). The high-grade Tellnes ilmenite mine where ilmenite is the main ore mineral and is easy to extract is not representative of the other Ti deposits in Europe, or even the rest of the world.

The global reserves of Ti-rich oxide minerals such as ilmenite ($FeTiO_3$) and rutile (TiO_2) are about 62 and 880 million tonnes, respectively, while the global reserves of vanadiferous/ V-bearing titanomagnetite deposits are 58 billion tonnes: i.e., far more than the reserves of the deposits where Ti is extracted from Ti-rich oxides, ilmenite and rutile. However, at present there is no commercial co-valorising of V and Ti from V-bearing titanomagnetite [Ti-V-Fe-(P)] deposits.

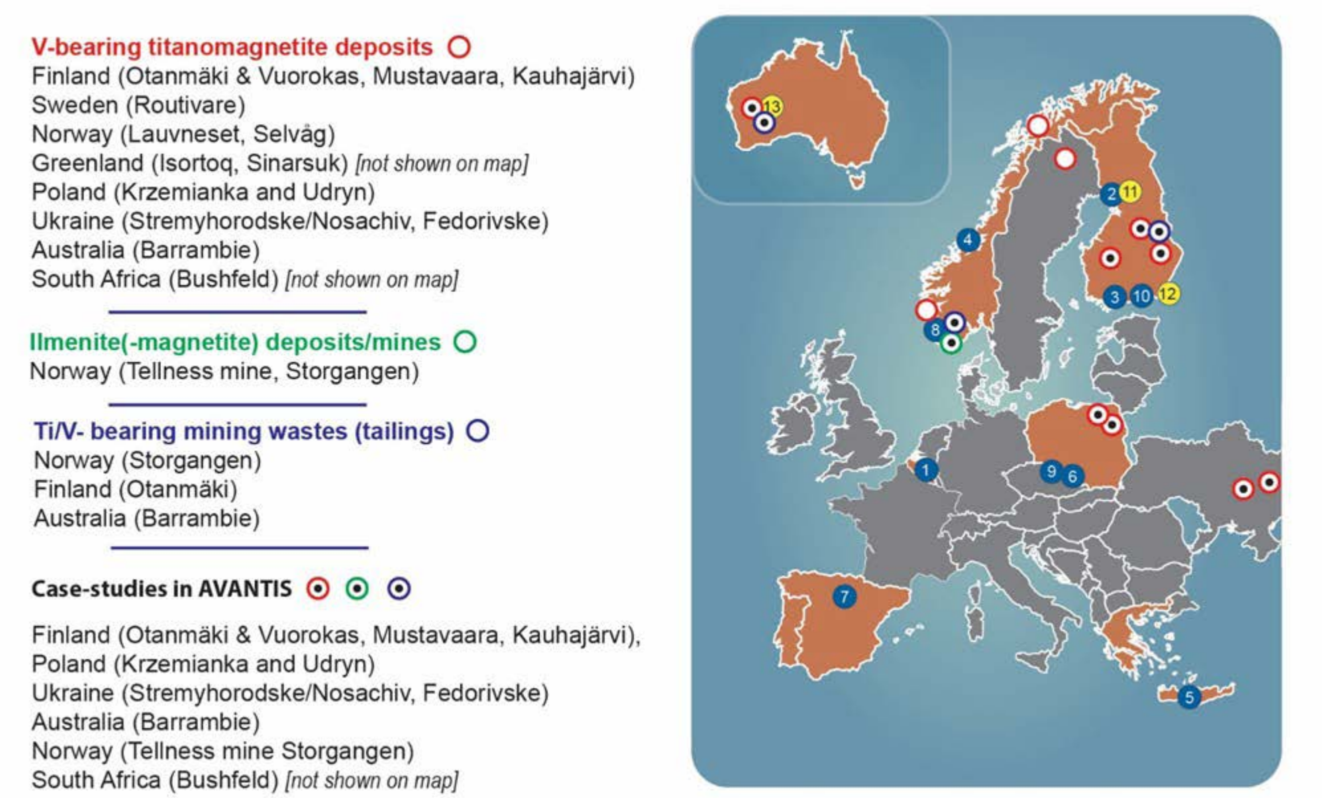

Fig 1. AVANTIS case studies.

To help achieve the benchmark of 10% domestic extraction in the EU's CRMA, the project AVANTIS will develop a low-carbon, multi-metal extraction approach for Europe's low-grade under/unexploited, vanadium-bearing titanomagnetite (Ti-V-Fe-(P)) deposits and mining wastes in Finland, Sweden, Norway, Poland and Ukraine. This novel "responsible mining" approach will extract two key CRMs V and Ti as pre-concentrates, which can be further processed by the relevant downstream industries to high-purity materials, e.g., all-V redox-flow battery (VRFB), Ti-V alloy. AVANTIS will also impact on the co-extraction of light rare earths and phosphorus from the rare-earth containing apatite concentrate.

AVANTIS APPROACH

Europe has a multitude of unexploited, low-grade V-bearing titanomagnetite deposits in Finland, Sweden, Greenland, Norway, Poland and Ukraine. However, these deposits have a complex "spiderweb-like" mineral assemblage (Fig. 2). Without selective blasting, selective fragmentation and pre-concentration technologies to separate the Ti-rich ilmenite grains from the V-bearing magnetite, these deposits are not economically viable.

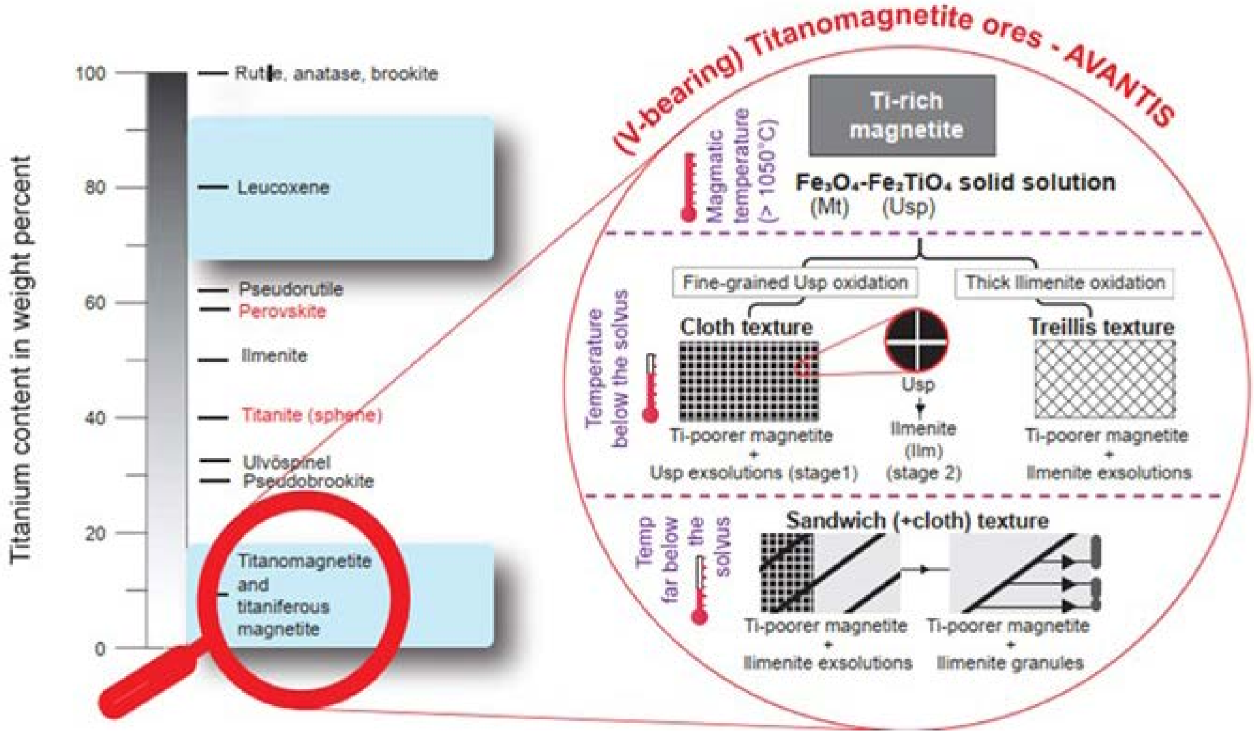

Fig 2. Complex mineral assemblage in vanadium-bearing titanomagnetite ores.

Supported by a bespoke forensic geometallurgy, AVANTIS develops a novel selective blasting approach that allows for rock excavation in view of increased mineral liberation at the blasting stage, and reduced energy demand in the crushing and grinding stages. In addition, AVANTIS designs tailored, water-free and water-lean pre-concentration technologies that can produce two distinct pre-concentrates: (1) ilmenite-rich, Ti-pre-concentrate and (2) ilmenite-free, V-pre-concentrate. The water-lean method is also tailored to process V/Ti-bearing mining wastes from historical/on-going operations. It is expected that the resulting flowsheets have a low net water consumption and reduced GHG intensity of extraction. AVANTIS strengthens the "responsible mining in Europe"-paradigm, increasing society's trust in domestic CRM production.

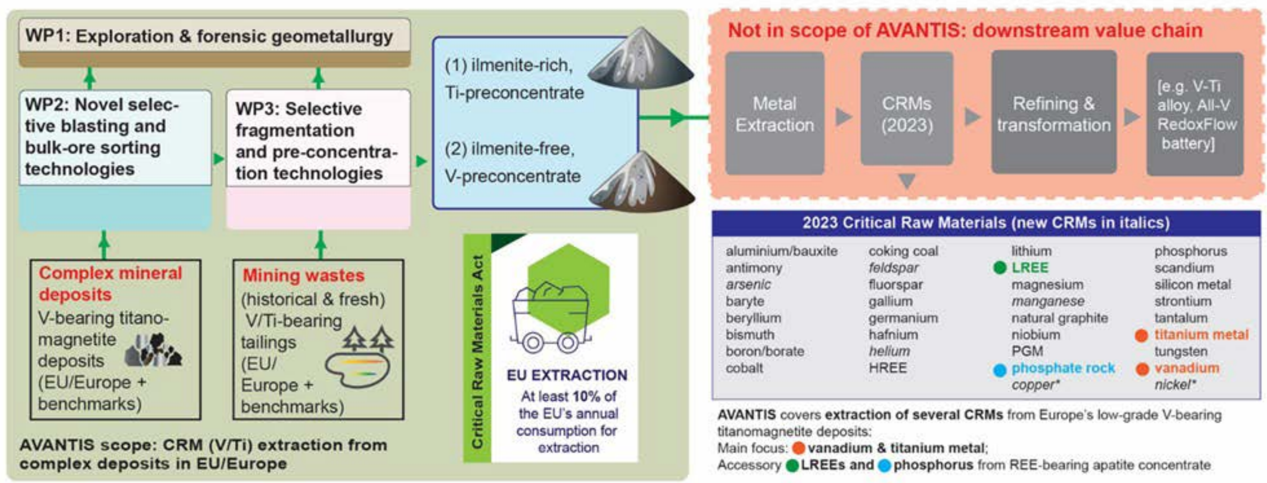

Fig 3. AVANTIS concept.

AVANTIS OBJECTIVES

- To develop and implement a forensic geometallurgy protocol for the extraction of Ti & V from V-bearing titanomagnetite deposits and V/Ti-bearing mining wastes, based on cutting-edge orebody knowledge.
- To advance towards a definition of optimum blasting parameters for rock excavation in V-bearing titanomagnetite ore that means (1) an increase in mineral liberation at the blasting stage; (2) a lower energy demand for the crushing and grinding stages
- To develop water-lean and/or water-free, advanced selective fragmentation and pre-concentration technologies that allow the separation of ilmenite and magnetite from V-bearing titanomagnetite ores and mining wastes, thereby producing two discrete pre-concentrates: ilmenite-rich, Ti-pre-concentrate and ilmenite-free, V-pre-concentrate.
- To develop an integrated environmental, health & safety, public-acceptance and techno-economic assessment for the tailored extraction routes of low-grade, EU-based vanadiferous titanomagnetite deposits and historical/fresh mine tailings.

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PERSEPHONE – AUTONOMOUS EXPLORATION AND EXTRACTION OF DEEP MINERAL DEPOSITS

by

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PERSEPHONE is a Horizon Europe project that aims to redefine how Europe explores and extracts deep and abandoned mineral deposits. The project's overarching ambition is to enable fully autonomous, sustainable, and digitalised mining operations that require no human presence in hazardous subterranean environments. This ambition directly supports the European Green Deal and the Critical Raw Materials Act by fostering technologies that reduce environmental impact, increase resource efficiency, and enhance safety and productivity.

The project aims to advance mining technology by tightly integrating advanced sensors with real-time analytics, enabling just-in-time decision-making across the exploration and extraction pipeline (see Fig. 1). At the heart of this transformation is the integration of robotic autonomy with advanced multi-modal sensing systems and real-time analytics, enabling machines to perform exploration, drilling, and ore characterisation independently. By integrating advanced sensor technologies – including 3D LiDAR, RGB-D cameras, Inertial Measurement Units (IMUs), multispectral and hyperspectral imaging, and Laser-Induced Breakdown Spectroscopy (LIBS) – into autonomous mining machines, PERSEPHONE aims to build dynamically updated digital twins of mining environments and ore bodies. These models will drive real-time decision-making, improve precision, reduce environmental impact, and optimise the entire mining value chain. The project also seeks to create modular, energy-efficient, and smaller-scale mining machines capable of navigating narrow drifts and operating autonomously under harsh subterranean conditions.

This project has received funding from the European Union's Horizon Europe Research and Innovation Programme under the Grant Agreement No.101138451.

A cornerstone of PERSEPHONE's autonomy framework is the development of terrain-aware mission planner, a graph-based planning system tailored to underground robotic exploration (Patel et al. 2025). Implemented within Work Package 4 (WP4), this planner enables robotic platforms to autonomously map, explore, and assess traversability in GPS-denied and harsh environments such as abandoned or deep mines. By integrating geometric and semantic traversability data – derived from 3D LiDAR and RGB-D sensors – into a hierarchical graph structure, path planner allows robots to make risk-aware decisions and share environmental understanding with other agents. Early results demonstrated that this planner enables efficient path planning and mission execution in simulated environments

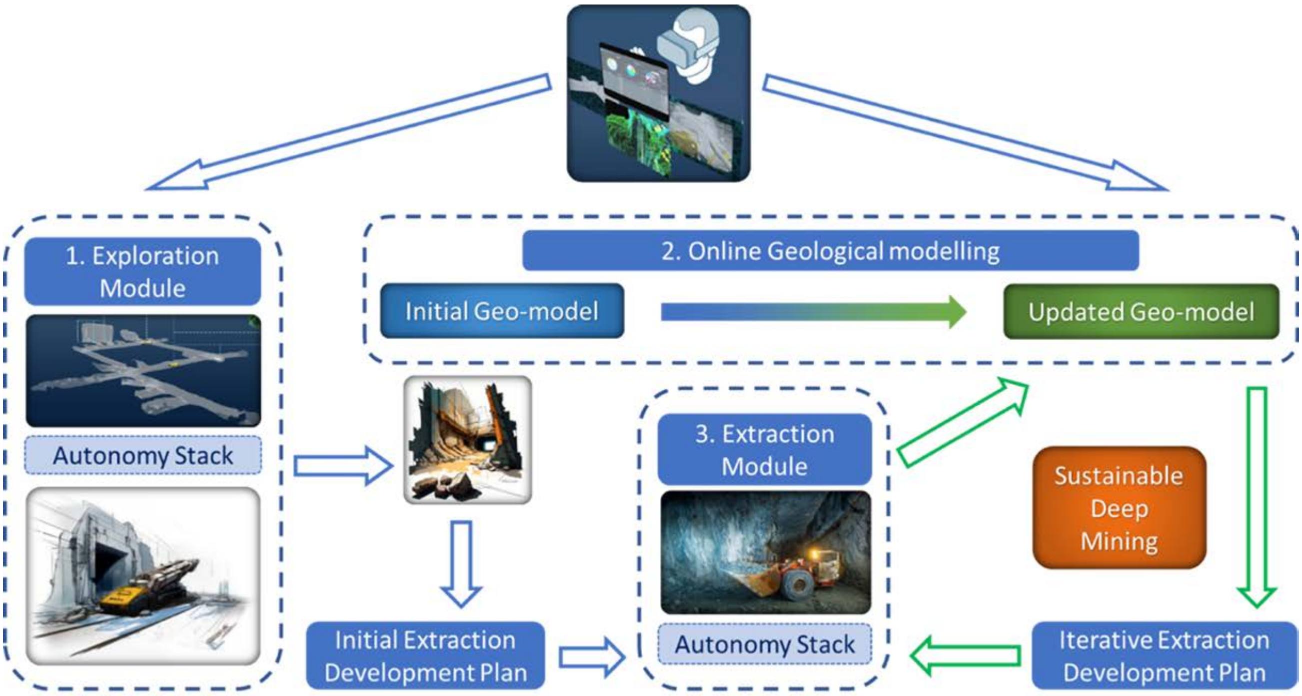

Fig. 1. PERSEPHONE approach towards the digitisation, automation, and robotization of mines.

constructed from real mine data. It also supports infrastructure-free multi-robot coordination via peer-to-peer communication and graph sharing, a critical capability for collaborative exploration missions in unstructured underground spaces.

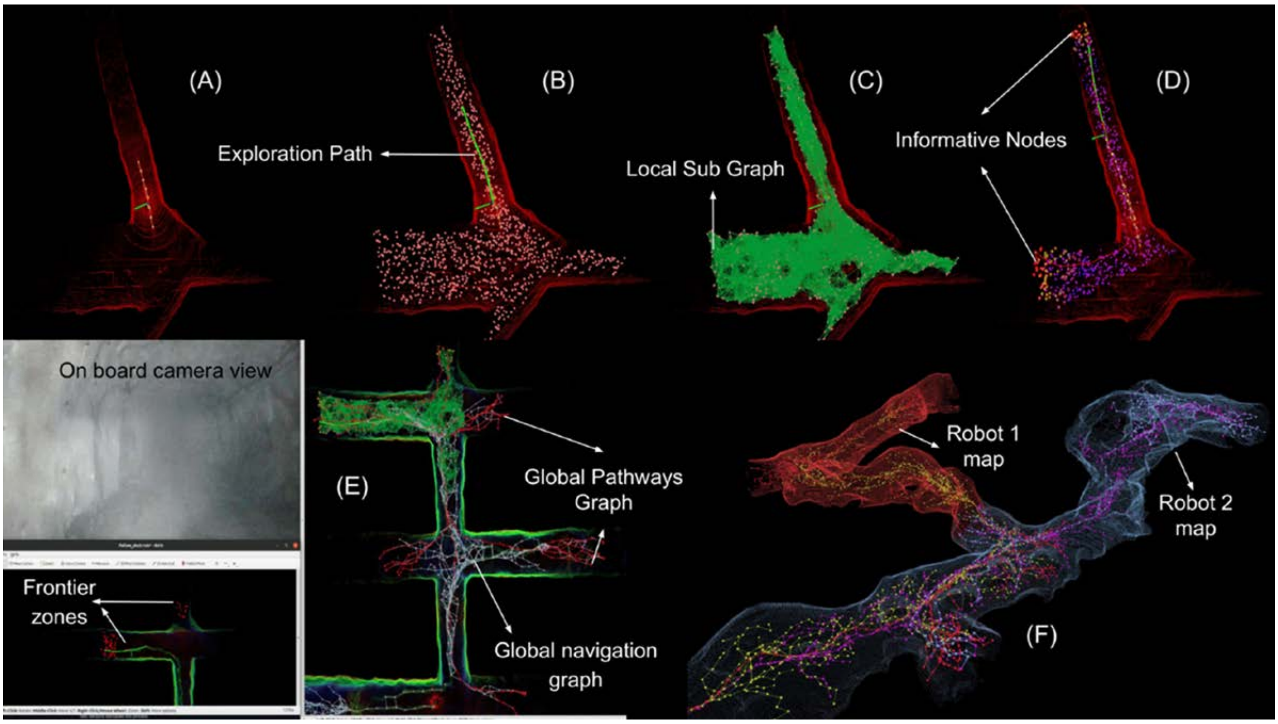

Fig. 2. Developments as part of novel path planning approach for autonomous navigation in known as well as unknown environments. The figure also highlights initial simulation results on set up of multi-machine coordination for 2 robots collaboratively.

These developments were grounded in extensive mine data collection and integration events. Two major campaigns were conducted at the Grecian Magnesite (GM) abandoned mine and the KGHM deep underground mine, where mobile robotic platforms equipped with autonomy and sensing payloads were deployed. The resulting point clouds and RGB-D scans were converted into detailed mesh models, which now serve as the basis for simulation environments. These environments are being used to test autonomous navigation, drilling alignment, sensor integration, and digital twin generation. In addition, multispectral and hyperspectral camaras along with the other sensors are also being field tested in the KGHM mines towards the accurate detection and localisation of the ore body. In parallel, indentation tests, LIBS slurry analysis, and early MWD logging were carried out and the data processed through the Elytica platform, developed by MRP to inform geological modelling workflows (WP7). Collaborative integration trials involving partners GSB, CUP, and EPI successfully tested multi-sensor payloads and validated early software-hardware synchronisation. Information about the project partners can be found at https://www.persephone-mining.eu/.

Together, these research activities, field validations, and software integrations represent a major step toward PERSEPHONE's mission to build a digitally connected, autonomous, and environmentally optimised mining ecosystem. The results lay a strong foundation for upcoming phases of the project, which will include full-scale integration of robotic platforms, autonomous mission execution in operational mine environments, and real-time feedback loops between machines and digital twins for dynamic mining optimisation. Through these efforts, PERSEPHONE is set to lead a new era in safe, sustainable, and data-driven mineral resource development in Europe.

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MSA-BASED CIRCULAR HYDROMETALLURGY FOR SUSTAINABLE, COST-EFFECTIVE PRODUCTION OF NMC CATHODE MATERIALS – CICERO

by

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On March 16, 2023, the European Commission (EC) published the Critical Raw Materials Act (CRMA) proposal, which establishes benchmarks along the strategic raw materials value chain and promotes the diversification of EU supplies. By targeting the domestic refining of three "strategic" battery-related critical raw materials (CRMs): nickel (Ni), cobalt (Co), and manganese (Mn), the CICERO project addresses the second CRMA benchmark: achieving a domestic processing or refining level exceeding 40%. To address the dual challenges posed by (a) Europe's reliance on a select few third countries (such as the Democratic Republic of the Congo, Indonesia, and China) for the supply of nickel, cobalt, and manganese for our NMC lithium-ion battery production, and (b) the subsequent environmental, health, and safety concerns associated with their extraction, CICERO has devised a sustainable and cost-effective refining methodology for Ni, Co, and Mn. This approach encompasses the downstream conversion of these metals into "made-in-Europe" NMC cathodes.

INTRODUCTION

The CICERO project is the first to develop a circular hydrometallurgical Ni, Co, and Mn processing/refining scheme that utilises methanesulphonic acid (MSA)

– a commercial, green, REACH-compliant, and affordable acid – instead of sulphuric acid (H_2SO_4). CICERO recovers, refines, and converts Ni, Co, and Mn from domestically available secondary raw materials: (a) post-mining raw materials (sulphide and laterite tailings) and (b) Ni/Co/Mn-bearing intermediates, including MSP, FeNi, Ni-matte, and Mn-anode sludge. To accomplish this objective, CICERO has developed a comprehensive suite of novel metallurgical unit processes for advanced MSA leaching and solution purification. These processes encompass the conversion of MSA to battery-grade MSA salts and the synthesis of NMC cathodes in MSA media. Additionally, sound reagent regeneration and iron recovery are implemented in accordance with the Twelve Principles of Circular Hydrometallurgy. This research is supported by advanced thermodynamic and kinetic modelling for solid-liquid and liquid-liquid equilibria pertinent to Ni/Co/Mn processing and refining in MSA media. CICERO introduces a novel paradigm for metallurgical processing and refining, thereby enhancing societal acceptance and trust in sustainable CRM production in Europe.

As outlined by Binnemans and Jones (2023), circular hydrometallurgical flowsheets employ closed-loop utilization of benign chemical reagents, such as MSA, in pursuit of zero-waste processes. Why MSA? The advantage of MSA over H_2SO_4, the "incumbent" acid for hydrometallurgy, is that the solubility of Ni, Co, Mn MSA salts in water is significantly higher than the corresponding sulphate salts, enabling more resource-efficient unit processes. Furthermore, MSA is a commercial, green, REACH-compliant, and reasonably priced acid (2000 USD/t) that is naturally occurring as part of the geochemical sulphur cycle. Consequently, it presents an industrially viable alternative to H_2SO_4 in the refining of Ni(/Co/Mn)-bearing post-mining wastes (tailings) and distinct intermediates (excluding MSP, FeNi, Ni-matte, and Mn-rich anode sludge from the zinc industry). These alternatives are being evaluated in CICERO (Fig. 1).

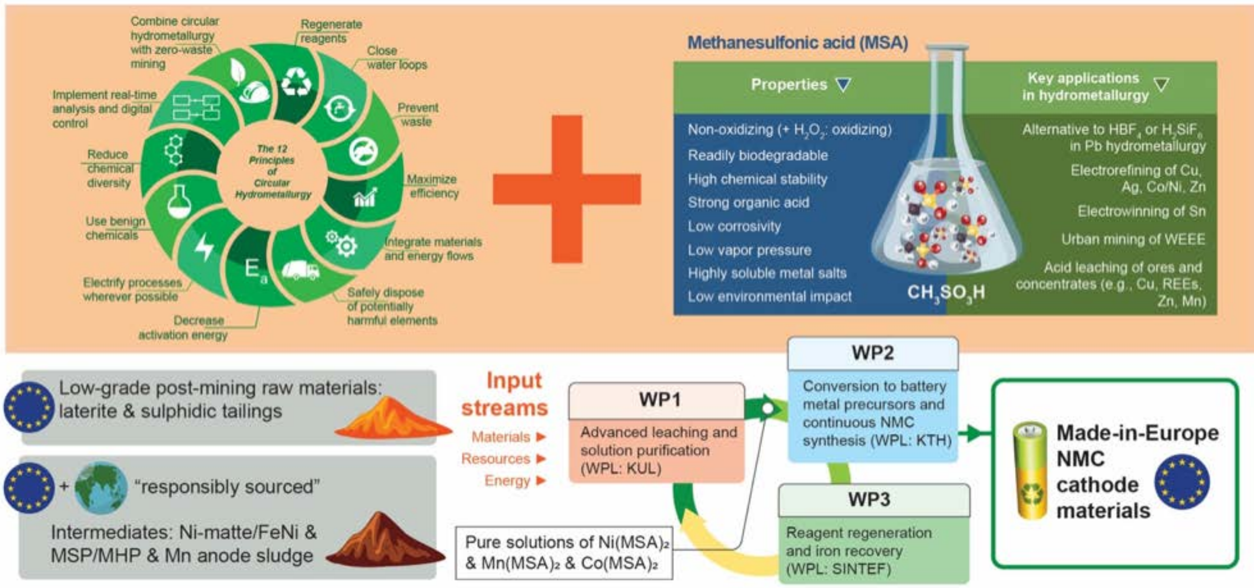

Fig. 1. CICERO integrates the 12 Principles of Circular Hydrometallurgy with the use of MSA to develop circular hydrometallurgical flowsheets converting a) tailings and b) intermediates into NMC cathode materials.

CICERO is more cost-effective than HPAL-type H_2SO_4 processes. The envisioned circular MSA-flowsheets will outperform the currently installed HPAL/H_2SO_4 technology in several aspects.

- Reduced installation process steps, leading to lower capital expenditures (CAPEX) and operational expenditures (OPEX).
- Reuse of MSA instead of H_2SO_4 as a consumable, resulting in lower OPEX.
- Absence of Na_2SO_4 waste generation, further reducing OPEX.
- Potential lower CAPEX for equipment during site construction.

PROJECT OVERVIEW

CICERO combines the 12 Principles of Circular Hydrometallurgy with the use of MSA to develop circular hydrometallurgical flowsheets converting (a) tailings and (b) intermediates into NMC cathode materials. It consists of 5 technical Work packages highlighting the circular use of MSA and 2 non-technical work packages.

WP1: Leaching & solution purification: Develop next-generation, scalable leaching setups and solution purification unit processes in MSA media. These processes, when strategically combined, can extract and recover Ni, Co, and Mn from (a) low-grade post-mining raw materials (tailings) and (b) distinct intermediates. This will result in pure solutions of $Ni(MSA)_2$, $Mn(MSA)_2$, and $Co(MSA)_2$ salts (or Ni, Mn, Co metals) for downstream NMC synthesis.
WP2: Conversion to NMC: Develop next-generation, scalable unit processes to convert pure solutions of $Ni(MSA)_2$, $Mn(MSA)_2$, and $Co(MSA)_2$ salts in battery-grade metals or solid MSA salts that are synthesised in NMC.
WP3 Reagent regeneration & Fe recovery: Develop scalable unit processes for the regeneration of reagents (including MSA) and the recovery of iron, thereby enabling the realisation of circular hydrometallurgical flowsheets.
WP4: Kinetic and thermodynamic modelling: Develop the theoretical framework for the kinetic modelling of bioleaching processes and the thermodynamic modelling of metal refining unit processes in MSA media.
WP5: Integrated assessment: Develop an integrated environmental, health and safety, and techno-economic assessment for novel unit processes and combined processing routes for Ni/Co/Mn-bearing (a) low-grade post-mining raw materials (tailings) and (b) distinct intermediates. The assessment should identify environmental and economic hotspots and propose improvements to process and energy efficiency.
WP6 clustering with other EU projects: To cluster CICERO with projects from past related calls (e.g., H2020/HE projects such as ENICON, EXCEED, Battery 2030) and present related calls (e.g., CL5-2023-D2-01, CL4-2023-RESILIENCE-01-03); to contribute to the objectives of Batteries Europe, the European Raw Materials Alliance and the CRMA; and to reach out to partners in Africa, the Mediterranean Region and the US in view of international cooperation and increased impacts.
WP7 Communication, dissemination and exploitation: To communicate CICERO's relevance, disseminate project results to diverse audiences, improve public awareness, acceptance, and trust in next-generation, circular hydrometallurgical processes for low-grade post-mining raw materials and distinct intermediates into NMC, and exploit project results to increase the EU battery supply chain's competitiveness through resource efficiency.

Work packages interconnections and CICERO's project methodology are graphically presented in Figure 2.

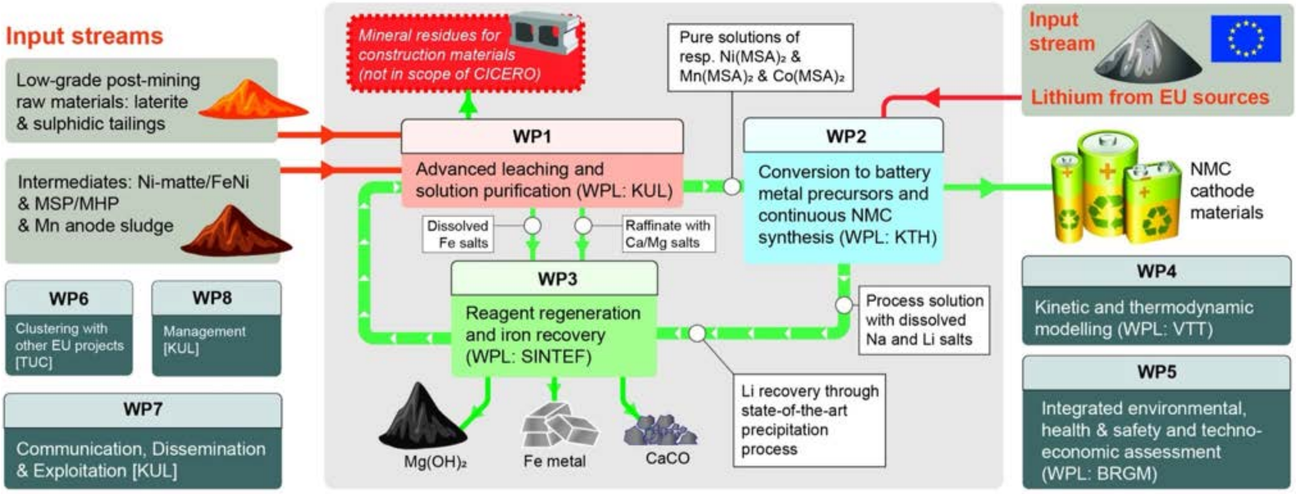

Fig. 2. CICERO project methodology highlighting the circular use of MSA.

CONCLUSIONS

CICERO tackles the twin problems Europe's dependence on a few third countries for refined Ni, Co and Mn salts. These metals are currently mined, processed at a massive ESG cost in DRC, Indonesia, and China. CICERO objective is to develop a sustainable and cost-effective processing & refining method for Ni, Co and Mn, and the downstream conversion into "made-in-Europe" NMC materials for Li-ion batteries.

ACKNOWLEDGEMENT

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HYPERSPECTRAL IMAGING: FROM EXPLORATION TO MINERAL SEPARATION

by

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This paper presents a continuation of ongoing research efforts in ore sorting technologies, emphasizing the integration of hyperspectral imaging (HSI) and cyber-physical infrastructures within Industry 4.0 and 5.0 frameworks. Building on prior developments in sensor-integrated ore sorters and mechatronic systems for mineral classification, the current work extends these foundations by analysing performance enhancements, modular adaptability, and the deployment of a lightweight deep learning model–P1CH–for real-time classification of hyperspectral data. The P1CH model has been embedded within existing systems to address the key challenge of rapid pixel-level classification across spectral dimensions in conveyor-based sorting environments. As mining operations increasingly adopt digital infrastructures, the demand for scalable, efficient, and autonomous sorting technologies has intensified. The limitations of traditional mechanical or visual inspection systems, particularly in accurately classifying spectrally similar materials, have motivated the adoption of sensor-based, AI-integrated frameworks. Hyperspectral imaging (HSI), when embedded within cyber-physical architectures, enables real-time identification of materials based on their spectral properties, significantly improving classification accuracy and reducing material loss (Sifnaios et al. 2023, Shaikh & Thörnberg 2022). The current work builds upon two system designs developed for mineral classification and sorting. These systems implemented a layered control framework and incorporated RGB, hyperspectral, X-ray fluorescence (XRF), and Raman sensors. The present paper consolidates and advances these approaches by emphasising real-time adaptability, model retraining mechanisms, and compatibility with embedded AI models, with an emphasis on operational robustness and deployment efficiency.

The development of a cyber-physical sorting system (CPSS) featured a structured, three-layer architecture comprising sensing, intelligence, and integration layers (Balakera et al. 2025a). The sensing layer incorporated RGB and hyperspectral cameras for capturing physical and spectral characteristics of mineral samples. This data was transmitted to a control layer where deep convolutional neural networks performed real-time material classification. An actuation mechanism, consisting of programmable air nozzles, executed classification-based sorting decisions.

Classification accuracy was further supported through the incorporation of offline Raman spectroscopy and XRF analysis for the characterisation and annotation of samples. These modalities served to validate and refine model performance through post hoc spectral feedback, ensuring robustness against material heterogeneity (Balakera et al. 2025a, Konstantinidis et al. 2023).

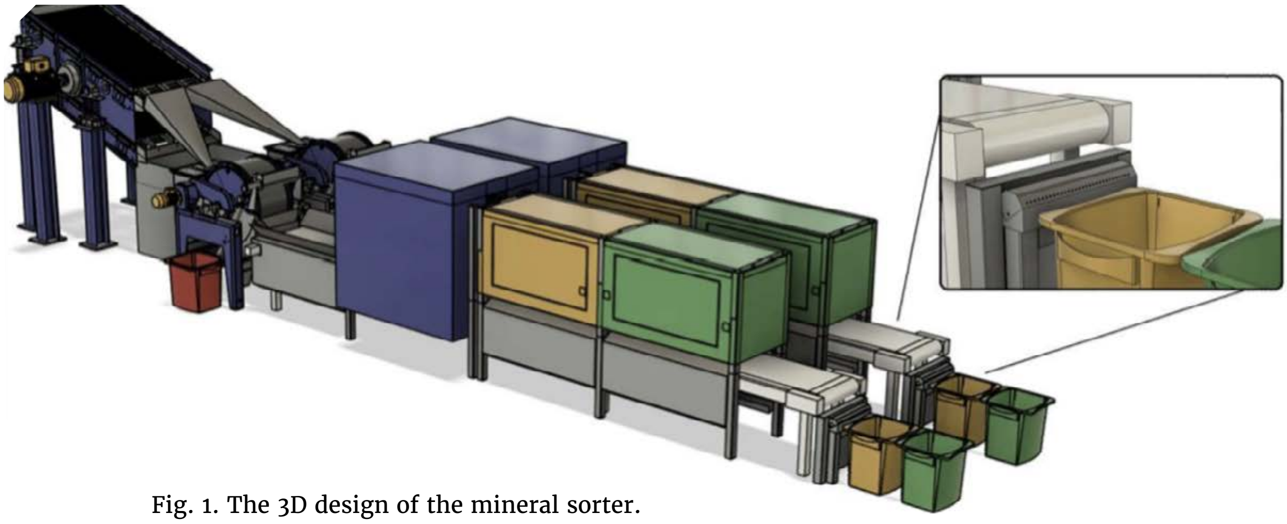

Fig. 1. The 3D design of the mineral sorter.

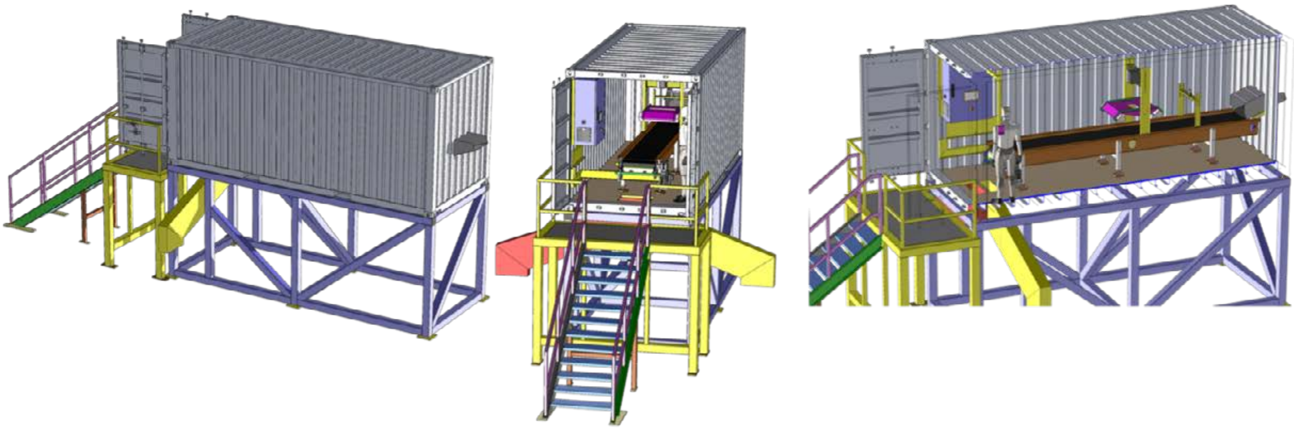

Fig. 2. End-to-end sorting solution, installed within a container.

At the system level, integration with cloud-based interfaces enabled remote monitoring and decision feedback, while compatibility with digital twin representations provided supervisory personnel with real-time process insights via mixed-reality interfaces (Balakera et al. 2025a). The CPSS was designed with modularity in mind, enabling deployment across different value chains through parameterization of control logic and sensor reconfiguration.

The self-adaptable mechatronic sorting system, depicted in Figure 1, while constructed specifically for magnesite separation from mixed ore streams (Balakera et al. 2025b), is expandable to various mineral streams and can be installed in the proposed containers in Figure 2, as an enclosed end-to-end solution. The system integrated pre-treatment units for size-based segregation, followed by a multi-sensor acquisition stage combining RGB and hyperspectral imaging units. A programmable logic controller (PLC) and industrial gateway facilitated control over conveyor dynamics and data streaming. Inline classification was managed through deep convolutional neural networks trained on hyperspectral data. The final sorting decision was executed via an air nozzle actuation array based on spatial coordinates and classification results. Parallel validation of mineral composition was conducted using handheld XRF and Raman spectroscopy to support periodic retraining and long-term generalization (Balakera et al. 2025b). Environmental robustness was prioritised in the design process, with the system exhibiting resistance to dust, variable lighting conditions, and sample occlusion. Finally, flexibility was ensured through a modular mechanical structure, which supported material-specific retrofitting and integration of additional sensor units without full system redesign.

To meet the demand for scalable, high-throughput pixel-level classification of hyperspectral data, the P1CH model was developed and integrated into the existing sorting architecture (Sifnaios et al. 2024). This 1D convolutional neural network was designed specifically for spectral vector inputs, employing residual blocks, batch normalisation, and dropout regularisation to enhance generalisation and training stability, as shown in Figure 2.

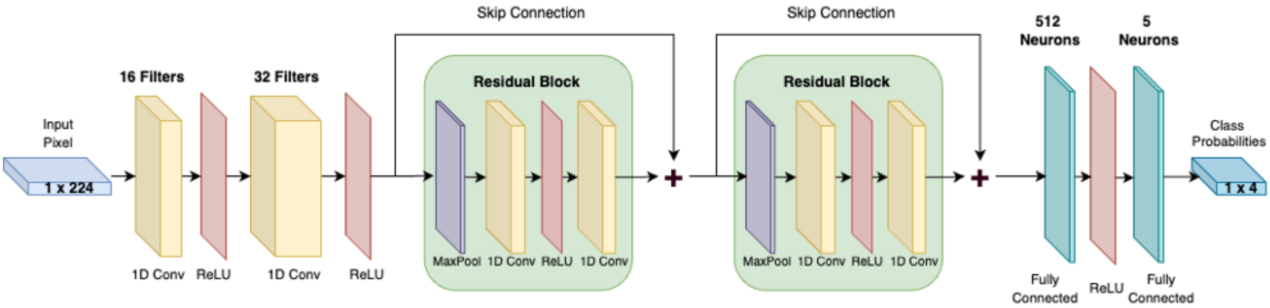

Fig. 3. The architecture of the P1CH classifier.

The model achieved classification accuracy exceeding 99% in controlled conditions and demonstrated high resilience to shape, colour, and illumination variability. Inference throughput surpassed 300 lines per second, enabling seamless real-time integration with conveyor systems. An example of the generated classification map is shown in Figure 3. The P1CH model addressed the primary bottleneck of hyperspectral analysis—classification latency—without compromising model size or deployment portability.

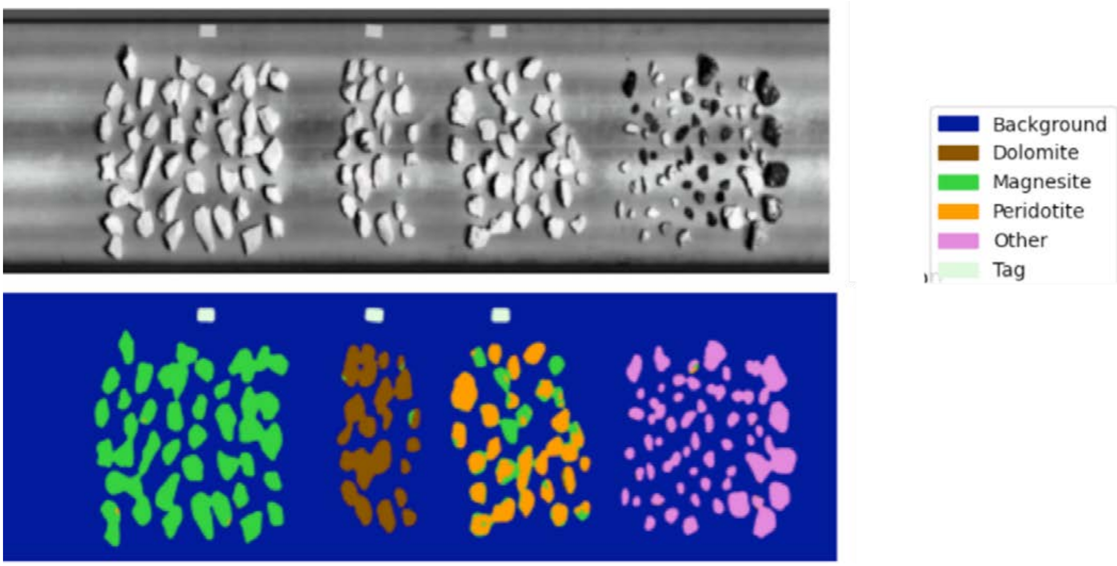

Fig. 4. The classification map generated by the P1CH classifier.

To accommodate operational constraints in field environments, the P1CH implementation relied on learned approximations for white and black reference normalization, thus avoiding dependency on calibration artifacts. This strategy ensured reliable spectral consistency while maintaining lightweight deployment requirements.

The current work consolidates and extends previously implemented ore sorting architectures by refining modularity, adaptability, and sensor integration strategies under the principles of Industry 4.0 and 5.0. Through the implementation of hybrid sensing (RGB, HSI, XRF, Raman), automated actuation, and cloud-integrated control logic, the developed systems provide a foundation for robust, autonomous mineral separation. The inclusion of real-time monitoring interfaces supports both operational oversight and human-in-the-loop correction, aligned with Industry 5.0 objectives. The development and integration of the P1CH model into this framework addressed the critical challenge of high-speed, pixel-level classification in hyperspectral mineral sorting. By unifying precision, throughput, and hardware compatibility, the solution enabled by the P1CH model establishes a benchmark for future intelligent classification platforms in the mining sector.

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REMHub – RARE EARTH AND MAGNETS HUB FOR A RESILIENT EUROPE

by

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Funded by Horizon EU, the new Rare Earth and Magnets Hub for resilient Europe (REMHub) project creates a cutting-edge digital innovation hub propelling EU excellence for Rare Earth Elements (REEs) and permanent magnets. This is a four-year project funded under the Horizon EU call HORIZON-CL4-2024-RESILIENCE-01-08 which started in October 2024. REMHub will develop, test and pilot novel technologies for exploration and primary production of rare earths and recovering rare earths from side streams to enhance supply security of REEs in EU. During the project, Re-X technologies (Recycle, Reuse, refurbish, and repurpose) for rare earths and valuable metals from end-of-life products will be developed, along with electric machine designs that facilitate permanent magnet recycling. The project will also identify and engage relevant stakeholders for developing REE and permanent magnet value chain in the EU. Furthermore, the innovation hub will facilitate the commercialization of novel technologies developed in the project, offering them as services on a digital platform. The project will also have dynamic communication and dissemination with the aim to involve and engage the public to develop trust and awareness related to REEs as well as to build capacity in EU. The hub targets transformative material sourcing for REEs and REE magnets, including traceability, digital twinning, and digital passport.

The project partners cover the entire REE value chain starting from mineral exploration, through mineral processing and refining to metal production and magnet making as well as recycling (Fig. 1).

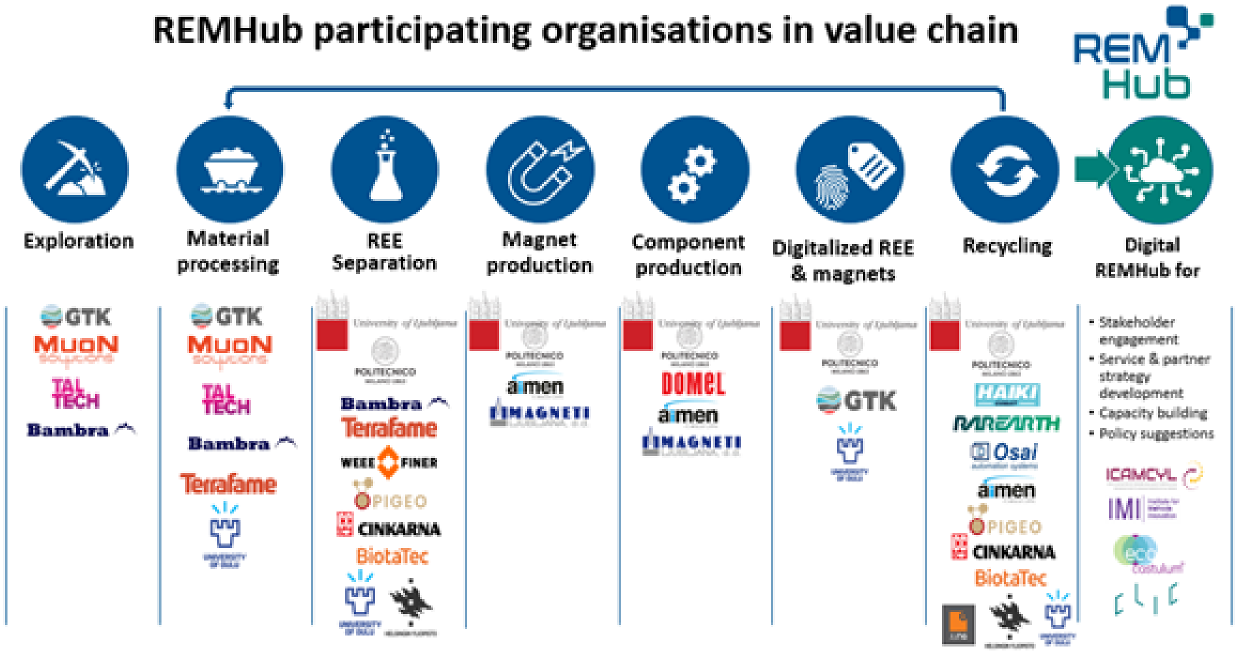

Fig. 1. REMHub project organizations in the REE and permanent magnets value chain.

The project incorporates safe and sustainable by design framework (SSbD) including design for Re-X (recycling, re-use, refurbishment, repurposing) approach integrating easy dismantling and circularity properties. REMHub will significantly improve the supply security of REEs in the EU and with the digital innovation hub accelerate the development of technologies and services to faster and easier market entry. The project consists of 24 partners from six EU countries (Estonia, Finland, Ireland, Italy, Slovenia, and Spain; Fig. 2).

Fig. 2. REMHub consortium.

The project has eight work packages. In work package 2 the project deals with novel technologies for mining and REEs processing. The technologies include involving ores crushing and grinding using two novel Continuously Compressing Crushers (CCCs) and innovative refining and separation technologies utilising ion-exchange (IX) and/or non-toxic chemical collector hybrid membrane-based technologies. In addition, muography for geophysical exploration and 4D scavenger technologies for wastewater treatment will be utilized in the project.

The primary goal of WP2, which is to develop proficient, cost-effective, and energy-efficient processing techniques for rare earth elements (REE) minerals, promoting sustainability in the EU value chain through life cycle assessment (LCA) analysis and geo-traceability. The tasks include developing innovative processing techniques using CCC (Continuously Compressing, Crusher) (Paasovaara et al. 2024) and hybrid ion-exchange (IX) membrane technologies (López et al. 2019) high concentrations of transition metals (iron, copper, zinc to reduce energy consumption and conserve water, as well as implementing geo-traceability methods to ensure sustainability. The project emphasizes collaboration between researchers, industry partners, and policymakers, aiming to deliver efficient, cost-effective, and environmentally sustainable processing techniques

In REMHub project, the radiation safety in the processing of rare earth metals, emphasizing the need to monitor radiation exposure levels to ensure they remain below the threshold (< 1Bq/g) is crucial. This includes planning for radiation safety assessments and risk management based on the uranium-238 (U-238) and thorium-232 (Th-232) content of samples. The assessment will be done to all related samples that are planned to be process at the sample location before they are brought to the processing facilities. At the University of Oulu, the radiation assessment will be continuously measured in the lab-scale before proceeding to the pilot-scale activities. Additionally, the Radiation and Nuclear Safety Authority (STUK) in Finland provides detailed guidelines on radiation safety measures, such as monitoring dose levels, implementing protective measures to minimize public exposure, and ensuring the proper use of protective equipment. These combined efforts aim to maintain radiation exposure as low as practically possible for both workers and the public.

Muography (MG) relies on the detection of atmospheric muon particles originating from cosmic rays' interaction with Earth's atmosphere. Naturally occurring muons traverse through any mediums following straight- line trajectories. However, as muons traverse through the medium, they undergo energy loss proportional to the mass density of the substances they encounter. This energy loss becomes more pronounced with higher material densities. The MG methodology (Holma et al. 2022, Zhang et al. 2020) requires that the muons first pass through the Object of Interest and then the detector, which is positioned below or adjacent to it. Muon detection survey is of a Novel Geophysical exploration technology (Holma & Arancibia 2022) currently developed and applied by Muon Solutions. REMHub will enable Muon Solutions to tailor the technology towards REE mineral deposits. MG surveys or simulations will be conducted and their results in 3D in combination with state-of-the-art geological 3D modelling and mineral characterisation will be interpreted. Muon survey applicability will be performed at the Korsnäs, Katajakangas and Kontioaho REE- deposits. Alternatives could imply using a muon detector on to image a zone of the deposit itself, furthermore software development can also be improved by using simulations on these test sites.

The 4D Scavenger® (4DS) proprietary technology owned by project partner Weeefiner offers unmatched efficiency and selectivity in metal recovery and water purification, turning waste and process water into valuable resources while improving the environment. 4DS technology is a versatile solution adept at water treatment and material recovery for extraordinarily complex water streams and liquids. Through Selective Laser Sintering (SLS 3D printing), 4DS can be tailored to achieve significantly faster reactions with improved efficiency and selectivity. 4DS overcomes the limitations of state-of-the-art wastewater technologies to effectively recover valuable metals. During REMHub project a pilot-scale demonstration will be developed with functionalities capable of trapping REEs from mining side streams.

By close cooperation of GTK, UOulu and Tallin University of Technology the project will enable intense collaboration between Finland and Estonia developing combined understanding of the respective deposits.

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ANGLO AMERICAN'S SAKATTI – A FUTURESMART MINE

by

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Anglo American is a global mining company focused on the responsible production of copper, premium iron ore and crop nutrients – future-enabling products that are essential for decarbonising the global economy, improving living standards, and food security. Our portfolio of world-class competitive operations provides metals and minerals needed for a cleaner, greener, more sustainable world and that meet the fast growing every day demands of billions of consumers. The Sakatti copper, nickel, platinum group metals (PGE) mine project in Northern Finland is to be company's new FutureSmart mine and demonstrates how responsibility can be incorporated into design, to minimise negative impacts.

The mitigation approach has been applied already from exploration stage. Together with drilling companies and other service providers several new procedures and techniques have been developed to minimize the impacts to nature. As an example, a closed water circuit technique for drilling was developed and has been used for years in all Sakatti drilling programs.

The biggest challenge in the Sakatti project is to design the operation so that it minimises the impacts on the Natura 2000 protected mire located above the orebody. The orebody is ca 200-1000 m below the surface. The mine will be fully underground, and no infrastructure will be placed on surface in the protected area. The industrial area, where the processing plant and other required infrastructure is placed, is located 5 km away, and will be connected to the orebody via a set of access tunnels which would reach the ore at a depth of about 500 m. Some of the primary crushing operations will be located underground, reducing the footprint of the mine.

The underground fleet will be fully electric, thus reducing the CO_2 emissions directly but also through reduced ventilation need. As the ore is exceptionally high-grade, it is possible to apply coarse waste rejection and coarse particle recovery techniques in processing. Consequently, the CO_2 emissions of Sakatti will be one of the lowest in base metals mining. Waste rock will be used in construction. The processing tailings will be divided into two streams. The high-sulphur tailings will be used as mine back-fill. Also, excess waste rock and 40% of the low-sulphur tailings will be placed underground. The remaining low sulphur tailings will be deposited using dry stacking, eliminating tailings pond risks and reducing water usage compared to normal wet tailings. The Sakatti project demonstrates how responsibility can be integrated into design from the outset.

MINOTAUR – A REVOLUTIONARY APPROACH TO SUSTAINABLE, SMART, AND RAPID MINERAL EXPLORATION

by

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The increasing demand for critical raw materials (CRMs) in Europe, driven by strategic initiatives like the European Green Deal, underscores the urgent need for more efficient and sustainable methods of mineral exploration. Traditional deep exploration drilling methods have proven to be slow, costly, environmentally intrusive, and insufficiently digitalised. In this context, the MINOTAUR, is a Horizon Europe project (https://www.minotaur-mining.eu) (Grant Agreement No. 101178775, https://cordis.europa.eu/project/id/101178775), introduces a revolutionary approach to autonomous robotic exploration drilling that integrates advanced geological science with pioneering technologies such as robotics, artificial intelligence (AI), and digital twin. MINOTAUR reimagines exploration drilling not as a linear mechanical process, but as an intelligent, source-seeking, and resource-mapping problem as depicted in Figure 1. The project introduces autonomous, robotised drilling and sensing technologies – termed MINOTAUR Explorers – capable of high-precision, directional drilling and branching. These robotic systems are equipped with a suite of invasive and non-invasive sensors, enabling in situ geophysical, geochemical, and geological characterisation without the need for extensive drill core retrieval. This approach aims to significantly reduce operational time, human involvement, and environmental footprint while increasing the reliability and resolution of subsurface data.

The need for innovation is driven by several critical challenges in current practices. First, conventional methods rely heavily on vertical drilling and the extraction of kilometres of core samples, which can take years and cost hundreds of millions of euros. Second, the digital transformation of exploratory processes remains limited, stalling data integration, slowing decision-making, and limiting predictive modelling capabilities. Additionally, the environmental degradation and visual impact caused by traditional methods hinder licensing procedures and erode social acceptance, further delaying resource development. MINOTAUR's interdisciplinary framework unites geoscience with advancements in AI, simulation engines, and high-resolution sensing technologies. By creating the digital twin, that continuously assimilates sensor data, producing a real-time, virtual representation of the subsurface that enhances decision-making and predictive accuracy. These models not only guide autonomous drilling in real time but also provide stakeholders with

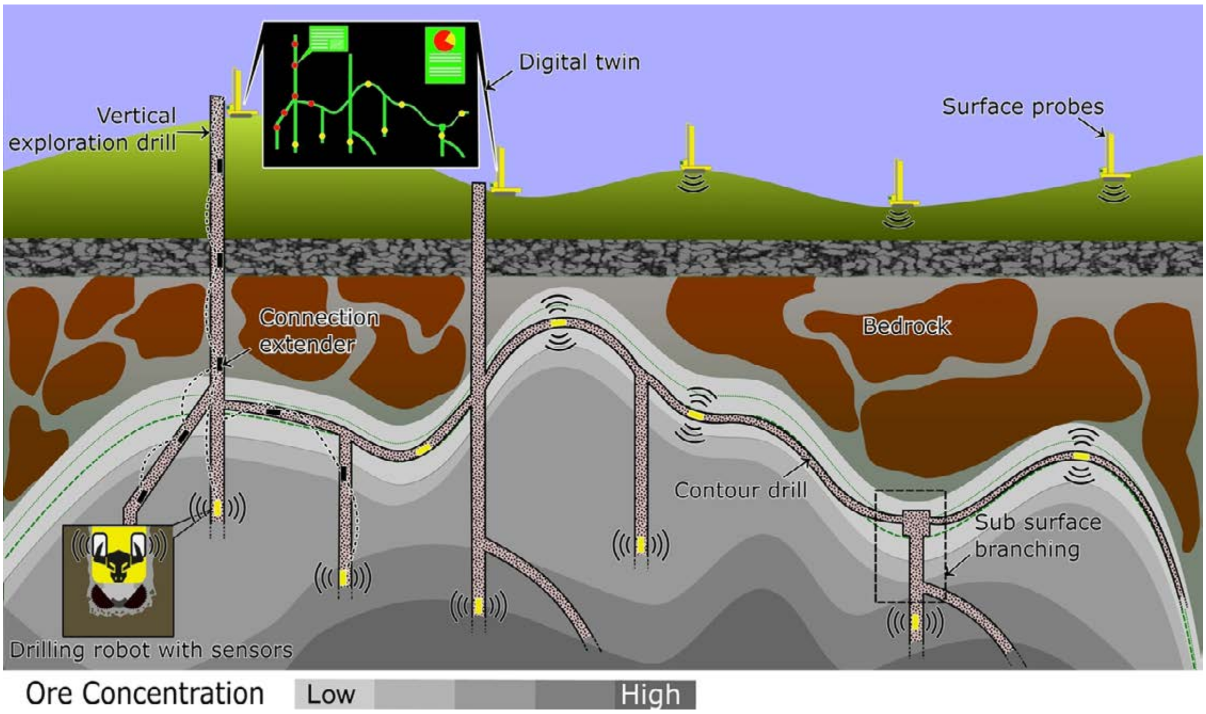

Fig. 1. MINOTAUR a conceptual overview of the novel exploration drilling.

reliable assessments of mineral potential, improving investment confidence and enabling faster transitions from exploration to exploitation.

MINOTAUR also contributes to environmental and social sustainability, ensuring that the technologies developed are not only efficient but also aligned with green investment standards. The anticipated outcomes include a significant reduction in capital and operational expenditure, improved social license to operate, and enhanced strategic autonomy for the European Union in securing critical raw material supply chains.

Towards achieving its objectives, the MINOTAUR project brings together a diverse consortium of leading universities, research institutions, industry experts, and policy organizations across Europe, including, Luleå University of Technology (project coordinator), Technical University of Denmark, Wrocław University of Science and Technology, IST-ID, University of Patras, Industrial Minerals Association Europe, Community Forged Innovation, and TERNA MAG S.A. Each partner contributes with unique expertise ranging from robotics and AI, geoscience, and sensing technologies to mining operations, policies, communication, and system integration. Together they will establish a new way to explore minerals ultimately paving the way for more efficient and sustainable resource management.

UNDERCOVER – ADVANCING INNOVATION IN DEEP MINERAL EXPLORATION

by

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INTRODUCTION

The UNDERCOVER (Unified Novel Deep ExploRation for Critical Ore discoVERy) exploration research project aims to revolutionize deep CRM exploration by extending the mineral systems concept to exploration-relevant spatial scales. UNDERCOVER is funded by the European Union Horizon Europe research and innovation funding programme. The consortium, comprising 16 partners from leading research institutes, academia, service providers, and industry, includes members from five European Union member states (Finland, Germany, France, the Czech Republic and Portugal), one from Namibia and one from Canada.

The project integrates advanced technologies developed by EU academia, research organisations and companies. It includes low-cost, full 3D lithosphere-scale passive seismic and magnetotelluric surveys for targeting prospective regions and regional scale mapping using innovative airborne techniques to identify exploration targets beyond 1 km depth. At the deposit scale, the project enhances cost efficiency for high-resolution, deeply penetrating seismic and EM methods for deposit study and environmental planning. Additionally, AI data integration and joint inversion methods are used to integrate multi-scale, multi-method geological, geochemical, and geochronological data, enabling 4D multi-scale analysis and modeling of mineralising systems. An integrated exploration strategy incorporates these technologies along with Environmental, Social, and Governance (ESG) studies to increase social acceptance and adoption of UNDERCOVER methodologies.

This new exploration strategy will emphasize the importance of using and integrating existing and new data, expert knowledge, and advanced modelling, inversion, and AI software solutions to optimize the predictive power of exploration models across various scales and stages. It will also address social and environmental issues. The introduction of UNFC guidelines is integral to our novel exploration strategy. Case studies in the Kuusamo Schist Belt (Finland), Iberian Pyrite Belt (Portugal), and Kalahari Copper Belt (Namibia) demonstrate the strategy by identifying several new deep exploration targets.

WORK PACKAGE 1: MINERAL SYSTEMS

WP1 deals with mineral systems in three pilot sites, selected to represent diversity in terms of critical mineral commodities, scale of mineralising systems and processes, and priorities in exploration targeting. This concept is based on an integrated study of the structural architecture of source regions, fluid/magma pathways and depositional sites across all scales, from crustal to intracrystalline, combined with data constraining the thermal and stress regimes as well as the origin, composition, and evolution of mineralizing fluids in the context of an understanding of the timing, or event history.

The goals of WP1 are: i) Refined conceptual understanding of mineral systems in 4D (evolution of the source-pathway-trap architecture through time); ii) Imaging of the present-day mineral system components in 3D, from lithosphere to deposit scale and, iii) The delineation of 2–4 new deep exploration targets by the end of the project.

The key tasks that will be performed include data compilation and an initial mineral system model for the three sites. Field data will be gathered regarding

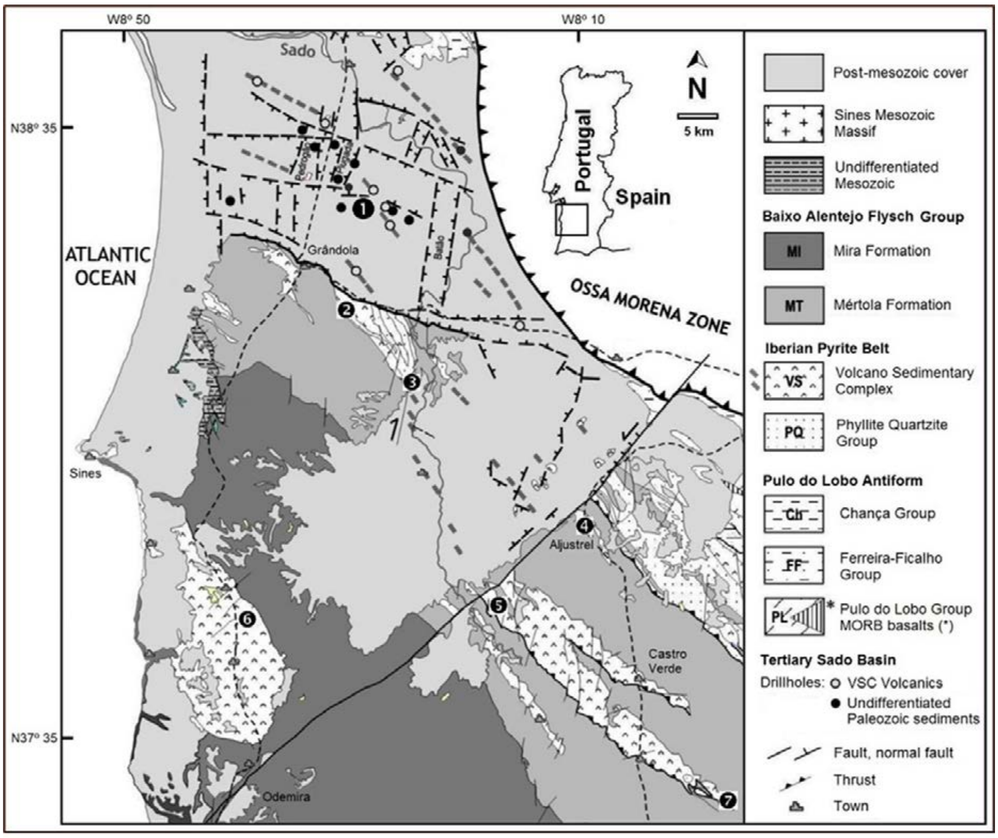


Fig. 1. Regional geological setting of the Lagoa Salgada deposit in the NW region of the Iberian Pyrite Belt: Massive sulfide deposits: 1. Lagoa Salgada, 2. Caveira, 3. Lousal, 4. Aljustrel, 5. Montinho, 6. Salgadinho, 7. Neves Corvo (Modified after Oliveira et al. 2005, 2013 in De Oliveira et al. 2011).

geochemistry at Kuusamo and geochronology at Kuusamo and in the Iberian Pyrite Belt. A 3D model will be built for these two sites. By the end of the project, and using all gathered information (including geophysical and data integration results from WP2 and WP3), a refined mineral system model will be produced for each of the three study areas, as well as a prospectivity model for the Kuusamo area.

The Iberian Pyrite Belt (Fig. 1) hosts almost 100 massive sulphide deposits including ca. 10 deposits over 100Mt. The Lagoa Salgada ore system has been chosen for study due to its unique characteristics: subvertical volcanic-hosted sulphide bodies affected by late-Variscan faults concealed beneath 80–200 m of Cenozoic sediments. Feasibility studies point to an inferred resource of 13 Mt at 2.44% Zn, 2.85% Pb, 0.34% Cu, 0.16% Sn, 0.75 ppm Au, 69.8 ppm Ag. Mineralization is present as primary massive and stockworks, with supergene enrichment as well.

The Kuusamo Schist Belt in northeastern Finland (Fig. 2) is a Paleoproterozoic basin that records a protracted history of volcanism and sedimentation, which was deformed and metamorphosed during the Svecofennian Orogeny. There has been an extensive history of exploration, focussing primarily on Au, U, Co and REE, with >20 Au-Co occurrences known, several of which have resources delineated. The rather unusual metal associations in the Kuusamo area reflect a diverse and complex mineralising event history. While there is a distinct structural control on the distribution of Au mineralisation, it is likely that salinity and redox contrasts in basinal fluids have had a significant influence on metal transport, a likely scenario being the evolution of Cl-rich brines diagenesis, overprinted and remobilised by more typical Au-bearing metamorphic fluids during convergent deformation.

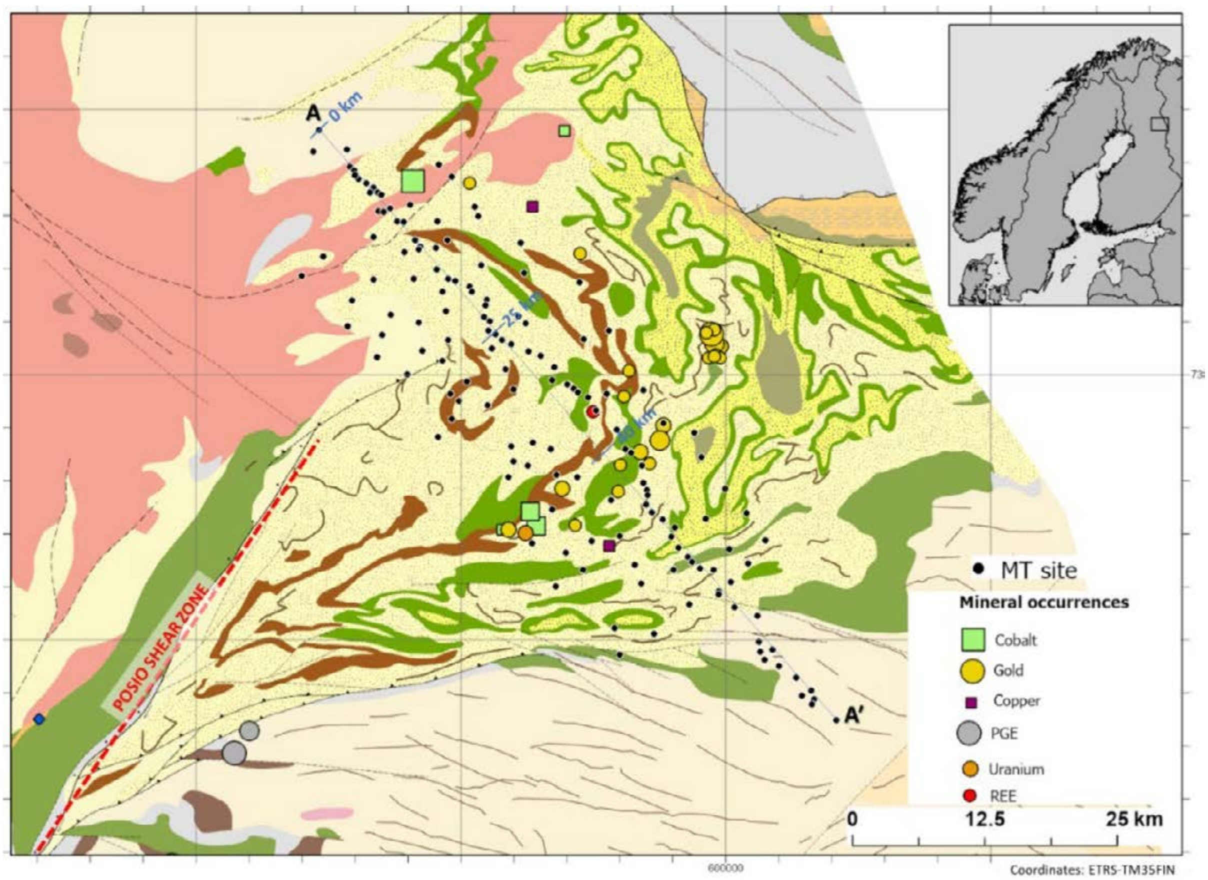
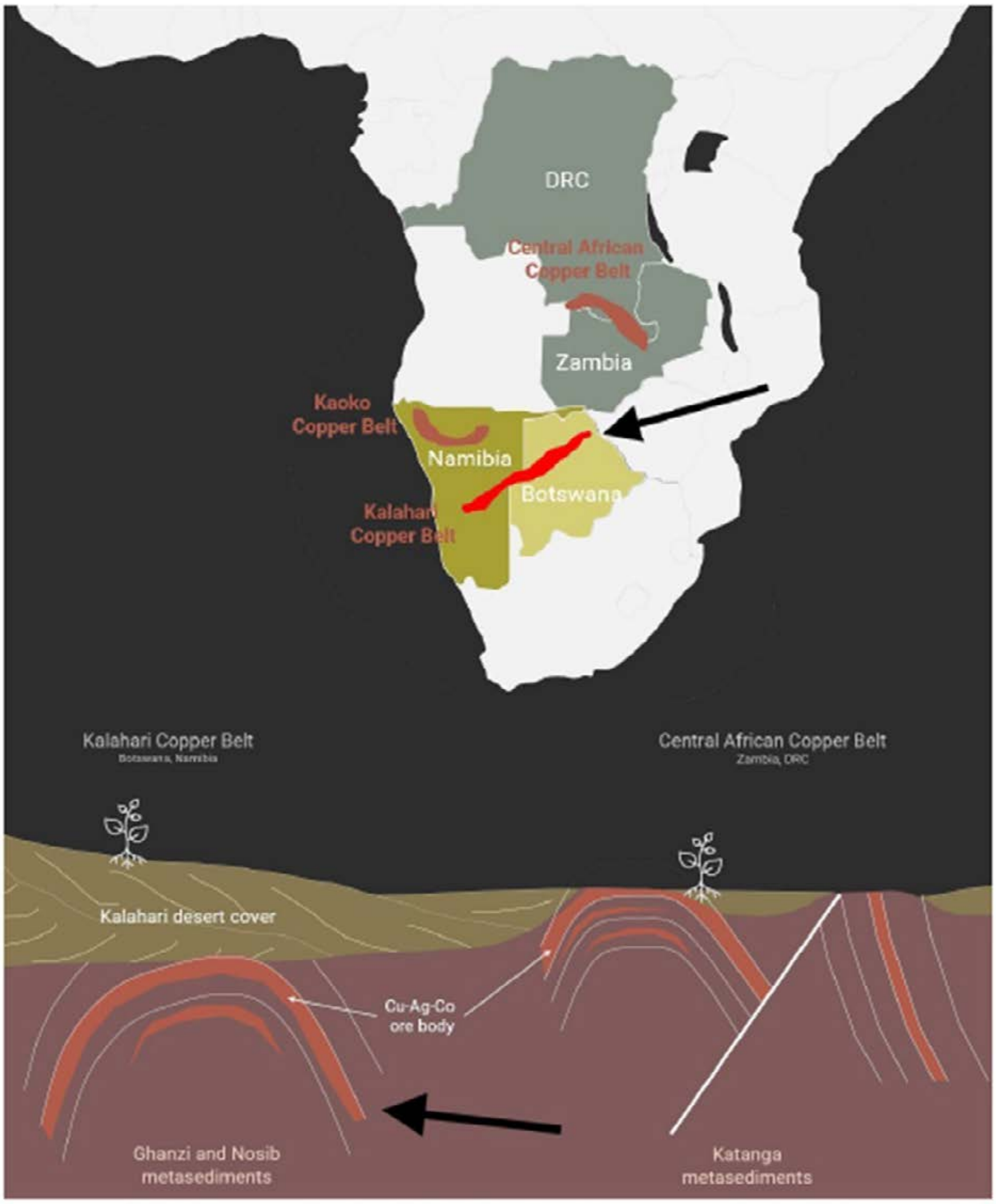


Fig. 2. Kuusamo Schist Belt, indicating the complex old interference geometry deforming siliclastic sediments (yellow), mafic lava flows (green) and sills (brown). Note the NE trend containing most Au deposits, within a regional antiform. Small black dots indicate measurement stations for the recent MT survey (Modified after Bedrock of Finland – DigiKP).

The Kalahari Copper Belt (Fig. 3) in Namibia is part of an extensive deformed Archean-Mesoproterozoic rift basin extending from Namibia to Botswana, characterised by sediment-hosted stratiform/stratabound copper mineral systems. The area has been chosen for inclusion in UNDERCOVER as representing regional scale exploration activity targeting structurally controlled mineralization in a folded terrain where bedrock is concealed by up to 100 m of unconsolidated sediments. By analogy with similar deposits elsewhere, mineralization is stratiform in nature, although modified and remobilized during deformation into large amplitude folds.



https://www.equivest.capital/post/next-major-copper-province-kalahari-copper-belt

Fig. 3. General location of Copper Belt in Namibia and regional interpreted cross-section.

WORK PACKAGE 2: GEOPHYSICS IN UNDERCOVER

The main task of WP2 is conducting as well as evaluating the geophysical surveys in the case study areas. Results from the different surveys will first be evaluated and models will be produced for each survey individually, after which the different datasets and survey scales will be combined and form a main input for the data integration approaches developed and applied within WP3. As project UNDERCOVER is aimed at developing approaches for identifying additional potential exploration targets through the combination and integration of different observational scales (see Fig. 4), we will conduct regional-scale (magnetotellurics and passive seismic), district-scale (semi-airborne and ground electromagnetics) as well as deposit-scale (active seismic, UAV and ground electromagnetics) geophysical surveys.

In the Kuusamo Schist Belt in Finland, we aim to improve our understanding of the regional-scale crustal architecture by collecting and evaluating magnetotelluric and passive seismic data in a roughly 180x150 km region. At the same time, we focus on a much smaller central area inside that wider region with techniques that have higher spatial resolution but a much lower depth penetration of ~1 km, among them semi-airborne and ground EM techniques as well as a large-N passive seismic survey.

For the Lagoa Salgada area in Portugal, we operate on the transition from regional to deposit scale, and combine semi-airborne electromagnetics with a 3D active seismic survey and the determination of depth-to-basement using passive seismic techniques. Lastly, in the Kalahari Copper Belt, we will explore the use of UAV-borne semi-airborne techniques to identify potential exploration targets buried under Kalahari sand cover.

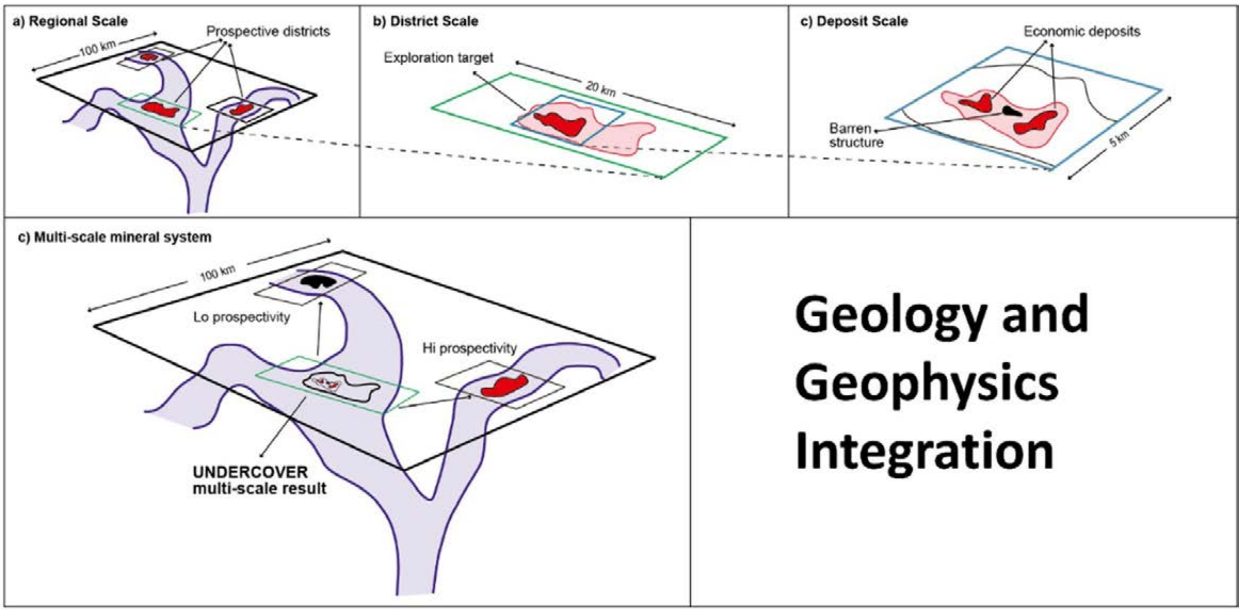


Fig. 4. UNDERCOVER multi-scale approach. a) Regional-scale surveying reveals lithosphere-scale mineral system components (blue) and identifies prospective districts. b) District-scale surveying includes use of new airborne methods detecting exploration targets to >1km depth. c) Deposit-scale studies to characterize the mineralizing processes, distinguishing ore bodies from uneconomic structures. d) Multi-scale mineral system modelling to transfer detailed knowledge to other districts.

WORK PACKAGE 3: INNOVATIVE DATA INTEGRATION

As a part of the comprehensive exploration workflow for Critical Raw Materials (CRMs), adaptable to both developed and remote regions, work package 3 focuses on integrating multi-source geoscientific data, geological, geophysical, geochemical, and petrophysical, into coherent 4D models of mineral systems. Two complementary approaches are developed: (1) joint 3D geological, geophysical, and petrophysical modelling, and (2) artificial intelligence (AI)-based data integration.

Detailed petrophysical analyses will be conducted on over 200 new samples to better understand how geophysical properties relate to mineral system components, accounting for lithology, alteration, metamorphism, and porosity. A multi-physics inversion workflow will be developed, extending existing tools (e.g., jif3D) to jointly invert magnetotelluric, gravity, magnetic, and seismic data. We will address both regional and deposit-scale modelling using advanced computational methods and multi-scale mesh techniques.

Artificial Intelligence (AI) tools will be used to improve automated or assist geological interpretation with the aim of delivering an AI tool capable of delineating zones of interest. To this end, neural networks will be trained on synthetic datasets to detect key mineral features, and deep learning models supporting quantitative seismic interpretation and lithofacies classification using drillhole and seismic data.

Together, these efforts enhance the accuracy, efficiency, and scalability of CRM exploration across Europe.

ADDITIONAL WORK PACKAGES

The technical work packages will be underpinned by a WP4, addressing environmental, social and governance aspects, and an overarching WP5, where all actions will be integrated into a concept for an integrated exploration workflow, including quantitative description of the value of each of the steps (Value of Information) and promotion of UNFC. Finally, WP6 is the package for dissemination, communication, and exploitation with the goal of bringing UNDERCOVER developments into wider use, and a WP7 for project management.

CONCLUSION

UNDERCOVER aims to integrate multi-scale geological and geophysical data into a system-level model to guide mineral exploration. It applies a range of data acquisition and interpretation techniques to demonstrate how optimized workflows can meet specific exploration needs. The project highlights the value of large-scale baseline data collected by public actors and introduces novel, deep-penetrating geophysical methods for wide-area coverage. Deposit characterisation efforts and mining planning relevant measurements, e.g., to describe and protect aquifer systems involve localized, high-resolution, deeply penetration data collection, which is correspondingly intense and expensive. UNDERCOVER seeks to reduce costs and improve efficiency across all scales. The sensible combination of sufficiently diverse and complex data to capture all relevant aspects of a mineral system is challenging and requires the development of cutting-edge data integration techniques.

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RESPONSIBLE MINING FOR ENERGY TRANSITION; ESG CHALLENGES AND OPPORTUNITIES IN AFRICA

by

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As the world rapidly shifts towards a greener, digital future, the demand for critical minerals such as cobalt, lithium, and rare earth elements has reached a strategic point (Secretariat, W.T.O. 2024). Africa, particularly the Democratic Republic of Congo (DRC), owns 70% of the world's cobalt and stands at the forefront of this supply (African Union Commission & OECD 2025). However, the existing frameworks for Environmental, Social, and Governance (ESG) reporting are not inclusive in a way that aligns with the realities and priorities of local communities. This paper, part of a master's thesis research, urgently presents a different approach to current ESG practices from an African-centred perspective, explores gaps in policy, and introduces a transformative framework known as Development, Stewardship, Reconciliation (DSR) as a culturally grounded alternative to conventional ESG approaches.

INTRODUCTION

The Organisation for Economic Cooperation and Development (OECD) and its 38 member countries are central in setting international standards for governance, economic growth, and environmental sustainability (OECD 2025a). While most African nations are not full OECD members, South Africa maintains close partnerships and contributes to OECD initiatives in Africa, particularly in governance, development, and trade (OECD 2025b).

In this context, collaborating with the Congolese people cannot be overstated. Through this collaboration, we can initiate a shift that genuinely benefits the population from an African perspective, specifically the Congolese. This vision resonates with the values held by many African communities, who are deeply committed to preserving their land and cultural heritage, acknowledging that the level of education in mining is still on its way and needs efforts to be built up.

As Mathias Cormann, Secretary-General of the OECD, emphasized: "*The OECD is a force for good in the world. All of us have a collective responsibility to use it to its full potential. Our core purpose, under our Convention, is to preserve individual liberty and to* *increase the economic and social well-being of our people. Our essential mission of the past to promote stronger, cleaner, fairer economic growth and to raise employment and living standards remains the critically important mission for the future" (OECD 2024).* In this approach, the Democratic Republic of Congo also holds the potential and the right to participate in and benefit from this collective responsibility. With the right frameworks and support, Congo can shape its sustainable development path while contributing meaningfully to global goals.

To engage with global initiatives, especially since their natural resources, such as cobalt, copper, and lithium, are crucial to the worldwide energy transition and digital transformation (IEA 2025, Willige 2025). Thus, Congo bears both rights and responsibilities. As the World Health Organization (2023) notes, we are all affected by climate change, making inclusive and collaborative action more urgent than ever.

Such inquiry calls for a deeper examination of strategies for integrating Environmental, Social, and Governance (ESG) principles in a way that is clearly understood and contextually relevant rather than merely applied as a checklist. ESG should not function as a compliance exercise but as a transformative framework rooted in deliberate, conscious, and culturally grounded implementation. A critical question thus emerges: Does ESG genuinely respond to the developmental needs of African nations, or does it primarily reflect the priorities of more advanced economies? Suppose ESG is to be meaningful in Africa, particularly in the Congolese context. How can it be implemented in a way that reflects local realities and contributes to sustainable, inclusive development? (Makhetha 2022, Sustainability Directory 2024).

This work investigates the limitations of ESG frameworks in African contexts, particularly within the mining sector. The study proposes rethinking sustainability through an African lens, emphasizing regenerative development, which focuses on restoring and replenishing resources and local agencies for a better future collaboration.

METHODOLOGY

For my master's thesis research, I interviewed 10 professionals in the mining and sustainability sectors, academics, and field experts across Africa, Canada, and Europe to gain various perspectives from within the industry. These conversations revealed a shared concern: ESG frameworks are often externally imposed since they are disconnected from local realities and frequently perceived as obligations rather than empowerment tools. This disconnect highlights the need to develop models that resonate with local values and understandings of sustainability.

To address this gap, I propose a new framework, DSR: Development, Stewardship, Reconciliation, which is part of the thesis research. DSR offers a reimagined approach to sustainability that replaces compliance with duty and extraction with regeneration. It is grounded in principles deeply rooted in African worldviews and ancestral knowledge systems. Its three foundational pillars are Environmental Stewardship, Social Justice, and Governance. Environmental Stewardship emphasises restoration and holistic land care. Social Justice prioritizes inclusive development and the safeguarding of cultural heritage. At the same time, governance advocates for transparent institutions and shared responsibility.

This model reframes sustainability not as a checklist but as an intrinsic duty embedded in community cohesion, cultural continuity, and long-term ecological balance. By grounding ESG principles in a local, culturally resonant framework, DSR enables more inclusive and practical engagement. For instance, in mining, DSR could mean restoring the land after extraction and ensuring that the local community benefits from the resource's education and that their cultural heritage is preserved. It creates space for communities to speak a shared language around sustainability, rooted in their values rather than imposed by external benchmarks.

Ultimately, aligning ESG implementation with African values through frameworks like DSR may offer a more inclusive and effective pathway toward sustainable development in resource-rich regions such as the Democratic Republic of Congo. This shift could bring a more optimistic future for all involved, including those in a more optimistic future for all involved, including those in a more advanced economy.

As part of the writing process, I used OpenAI's ChatGPT (May 2025 version) to refine the clarity and articulation of this paper. All critical analyses, Interpretations, and conclusions presented are my own.

DISCUSSION

We cannot decouple the growing focus on energy transition technologies. AI, quantum computing, big data, and renewables are increasingly integrated into the global energy transition, which stems from the ethical sourcing of minerals. Current ESG reporting mechanisms are designed primarily for Western audiences and often function as external obligations rather than internalized values (Ghaemi Asl et al. 2024). Transformation, however, must originate from within local contexts, starting at a level of understanding accessible to the communities involved.

This paper argues for a cross-collaboration between ESG and DSR frameworks, allowing both to benefit from each other. ESG provides structure and international benchmarks, while DSR embeds ethical, cultural, and communal dimensions into resource governance.

CONCLUSION

While ESG frameworks are applicable, African mining practices should be attuned to local contexts. The path forward requires a paradigm shift that embraces local narratives and worldviews. A successful transition to responsible mining in Africa must not merely adopt international ESG standards but redefine them through African wisdom and lived experience. True sustainability in mining will only apply when local communities do not just consult but are co-authors of the frameworks that govern their land and future.

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THE SOCIAL IMPACTS OF MINING: A FOLLOW-UP RESEARCH IN NORTHERN FINLAND

by

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WHAT ARE THE SOCIAL IMPACTS OF MINING? HOW CAN WE FOLLOW UP ON THE CHANGES IN SOCIAL IMPACTS?

The environmental impacts of mining are assessed before mining projects take place, and these impacts are monitored according to the environmental permit granted. Social impacts are also often assessed as part of the environmental impact assessment. However, in Finland, there is no legislative requirement to follow up or monitor the social impacts during or after mining projects (Kokko et al. 2013).

Social impacts can be both positive and negative, short- or long-term, and vary in scale. These impacts may arise from changes in the environment or in the socioeconomic status of a community (Vanclay et al. 2015, Kuisma & Suopajärvi 2017). Social impacts are related to, for example, livelihoods, employment, well-being, lifestyle, culture, and the environment. The scale and type of impacts, as well as the location of the mine relative to other activities and land-use purposes, can affect the nature of these impacts. For instance, mining in an urban area may have different social impacts than mining in an environmentally protected area or in a region that is critical for other livelihood activities.

This poster introduces follow-up research on the social impacts of mining in Sodankylä, focusing on the local community's residents and the impacts they have observed and experienced. In Sodankylä, industrial-scale mining is the dominant sector offering private sector jobs. One large mining project is currently in the operational phase, while two other significant projects are in the permitting phase.

The research is answering to the following questions: how the impacts of mining are observed and experienced by the local residents in Sodankylä? What kind of changes can be seen when comparing the data and analyses of surveys? How social impacts and the changes can be understood in the context of the local community's agreed socially sustainable development goals? The research is also contributing to the discussion on how the social impacts of mining or other large-scale industrial projects can be studied with the longitudinal or follow-up research perspective.

The survey on the social impacts of mining has been conducted four times by the University of Lapland (Kuisma & Suopajärvi 2017, Saariniemi 2018, Tulilehto & Suopajärvi 2021, 2023), and a fifth survey is in progress. These regular follow-up surveys on the social impacts of mining at local level are unique in the Finnish context.

The survey was designed in collaboration with the local municipality, stakeholders, and mining and exploration companies in Sodankylä. The goal of this follow-up research is to gather scientific knowledge and data on the social impacts of mining as experienced and observed by local people. It also aims to provide valuable information for local actors to aid in planning and problem-solving on challenges and opportunities.

The quantitative data from the follow-up research surveys are analysed using multivariate techniques, such as factor analysis. As Silen (2021) notes, factor analysis is a commonly used method in sociological research and was originally developed for studying human behaviour. The surveys included also open-ended questions for the qualitative analyses.

The follow-up research on social impacts is part of the social impact management plan outlined in the "Mining Programme" of Sodankylä, developed together with local stakeholders, the municipality, and the mining sector actors. The social impact management plan was formulated trough a collaborative planning process together local stakeholders, municipality and the mining sector actors. (Suopajärvi & Kantola 2020)

To develop sustainable and effective social impact assessment methods for mining in the local context, where many of the direct impacts are experienced firsthand, there is a need for scientific knowledge and information about these impacts. The challenge is that as Missimer et al. (2017) says, many argue that sustainability is a "wicked" problem, where uncertainty is high and where there is debate over values and also how the solutions are not obvious.

However, as Sairinen et al. (2021) conclude, following Barrow (2010), scientific research on social impacts can help model how individuals, groups, and communities adapt to changes and how mining affects the quality of life and well-being of populations on local level.

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DEVELOPMENT OF THE MINING SECTOR IN LAPLAND, NORTHERN OSTROBOTHNIA, AND KAINUU

by

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The global shift toward clean energy systems, the electrification of transportation, and sustainable development trajectories is increasingly contingent upon secure and strategic access to critical raw materials. Within the European context, enhancing self-sufficiency in raw material sourcing has become imperative for safeguarding the industrial foundations necessary to facilitate the green transition. In response, Eastern and Northern Finland have intensified multilevel cooperation among regional, national, and international actors to promote the sustainable utilisation of mineral resources.

At the regional scale, Mining Hubs play a central role in advancing the mineral industry by fostering innovation and facilitating coordination among stakeholders. Complementing these efforts, Finland's newly formulated mineral strategy prioritises the development of the mineral and battery value chain, supports the principles of the circular economy, and contributes to enabling both clean and digital transitions. At the supranational level, the European Union's Critical Raw Materials Act aims to secure a resilient, diversified, and environmentally sustainable raw material supply chain while enhancing the EU's strategic autonomy.

Within this multi-scalar governance framework, research and innovation (R&I) institutions and training organisations serve as critical enablers of cross-sectoral collaboration. Notably, key academic and research institutions—including the Geological Survey of Finland, the University of Oulu, and Kajaani University of Applied Sciences—have joined forces in the project *Development of the mining sector in Lapland, Northern Ostrobothnia, and Kainuu*. Launched in September 2024 and spanning two years, the initiative is designed to strengthen regional competencies, foster R&I-driven innovation, and enhance industrial engagement, thereby reinforcing the mining sector's contribution to sustainable development in Finland's northern regions.

The project directly addresses the recognised need to deepen inter-institutional and cross-regional cooperation within the mining sector of Eastern and Northern Finland, while also sustaining dialogue aimed at shaping EU-level policy frameworks that reflect the specific conditions and capacities of these mining regions. To fulfill its objectives, the project will organise thematic workshops and ensure active participation in both national and international conferences and professional events, thereby cultivating networks, promoting knowledge exchange, and reinforcing strategic cooperation.

In general level, regional collaboration is strengthened through workshops in participating regions, emphasising key themes and facilitating connections between industry experts, companies, and external stakeholders. Efforts are aligned with regional specialisation programs and existing initiatives, while joint events with mining industry development organisations further enhance cooperation. International and EU collaboration involves engaging with EU strategies such as the Critical Raw Materials Act and the Green Deal, assessing their regional impacts, and identifying opportunities. Regional expertise and businesses are promoted at European and global mining events, and meetings are organised with EU Commission representatives to explore further collaboration within the Nordic mining industry. Research and development efforts contribute to the National Research Agenda for Critical Raw Materials and foster new mining-related project initiatives, emphasising company participation. Expertise is enhanced through seminars, best practice dissemination, and the creation of training materials. Project management and communication ensure smooth administration, reporting, and outreach.

The project has been co-funded by the European Union Just Transition Fund (JTF) in collaboration with participating organisations. The total budget is approximately 517 000€ and implementation period from September 2024 to August 2026.

USE OF REMOTE SENSING ALONG MINING LIFE CYCLE – TECHNOLOGICAL, SOCIAL AND POLICY ASPECTS

by

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The S34I – Secure And Sustainable Supply Of Raw Materials For EU Industry project developed applications using remote sensing data throughout the mining life cycle, including exploration, extraction, and closure phases. Fourteen methods were created using satellite and drone data to address various aspects such as mapping critical raw materials (CRM), monitoring Acid Mine Drainage (AMD), and assessing stability.

The technological aspects of the project involved collecting data from drone multispectral sensors, Sentinel-2, and WorldView-3 satellites. Machine learning techniques, both supervised (logistic regression, random forest, k-nearest neighbour, multilayer perceptron) and unsupervised (Self-organising Map (SOM), K-means clustering), were employed to analyse the data.

A case study in Outokumpu, Finland, highlighted the project's practical applications. The research demonstrated the effectiveness of remote sensing data for long-term monitoring of AMD impacts. Integrating Sentinel-2 and WorldView-3 data significantly enhanced machine learning model performance for AMD classification and pH prediction.

The project also addresses policy recommendations for implementing Earth Observation (EO) monitoring methods in mining activities. It emphasises the need for clear policy objectives, cross-sector collaboration, and the development of fit-for-purpose services. National strategies should embed EO technologies across the mining life cycle, supported by capacity building, open data policies. Increasing public awareness and accessibility of EO-based tools for monitoring extractive activities is also recommended.

CRITICAL RAW MATERIAL OVERLAP WITH PROTECTED AREAS BY COUNTRY AND COMMODITY

by

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Mining for raw materials is crucial for society, but it can conflict with preserving biodiversity in protected areas (PAs). As demand for raw materials grows, especially those deemed critical (CRMs, European Commission 2023), there is increasing pressure to extract resources from protected lands. Balancing resource extraction with conservation efforts is essential to minimise environmental impact and protect these valuable ecosystems. PAs currently cover approximately 24% of the land area in European Union (EU) countries. Consequently, any raw material occurrence on land can be expected to coincide, at least to some extent, with PAs. However, there are differences between EU countries in terms of PA coverage.

Within the CrItical RAw materials extraction in enviroNmentally protected areas (CIRAN) -project, this sensitive topic is researched. In the study presented here, we provide comparable information on the overlap between CRMs and PAs in a European wide scale which should be taken into account by, e.g., regulators to provide realistic guidelines for raw material extraction. Furthermore, the location of a raw material occurrence is, when considering ore deposits, controlled by geological processes. Consequently, we have conducted a spatial analysis of overlap between CRMs and PAs in Europe where individual countries and CRM commodities can be compared in terms of how much they overlap with each other. As spatial data for PAs we use Natura 2000 (European Environment Agency and European Commission 2024), Emerald Network (European Environment Agency 2024) and common database on designated areas (CDDA, European Environment Agency (2022)). These datasets consist of polygon data, i.e. spatial extents of individual PAs in EU and European environment information and observation network countries. By merging them together, we generate a spatial dataset of PAs covering much of Europe with up-to-date designations.

To locate CRM occurrences, we use data provided in European geological data infrastructure (EGDI, European Geological Data Infrastructure (EGDI) (2024)). Dataset named, Critical raw material occurrence points 2023, contains CRM occurrence data in EU countries and some outside EU (GEUS 2023). The dataset has been created as a collaboration in Horizon Europe projects where data from individual geological country surveys has been harmonized and integrated (Mintell4EU project 2021, FRAME project 2022, Whitehead et al. 2021).

Two primary methods for calculating the overlap of CRM occurrences with PAs were used. The first method consisted of calculating the distance to the nearest

PA for each CRM occurrence (Fig. 1a). In the second method, we calculate the proportion of PA that covers an area 5 km from a CRM occurrence (Fig. 1b).

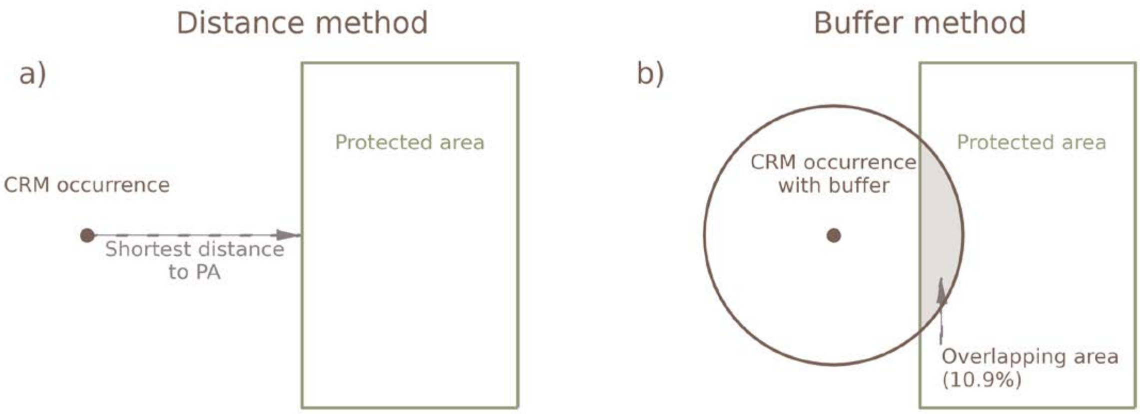

Fig. 1. Diagram showcasing the a) distance and b) buffer strategies for evaluating CRM occurrence and PA overlap. The example CRM buffer region overlaps 10.9% with the PA.

Most countries have close to the average (2481.36 m), calculated from all countries, or lower mean distances to the nearest PA (Fig. 2). Countries with mean distances higher than the average include, from the EU, only Poland and Portugal. Albania, Bosnia and Herzegovina, Montenegro and Serbia have the highest mean distances to PAs. However, these countries have low CRM occurrence counts (n), possibly indicating lacking data.

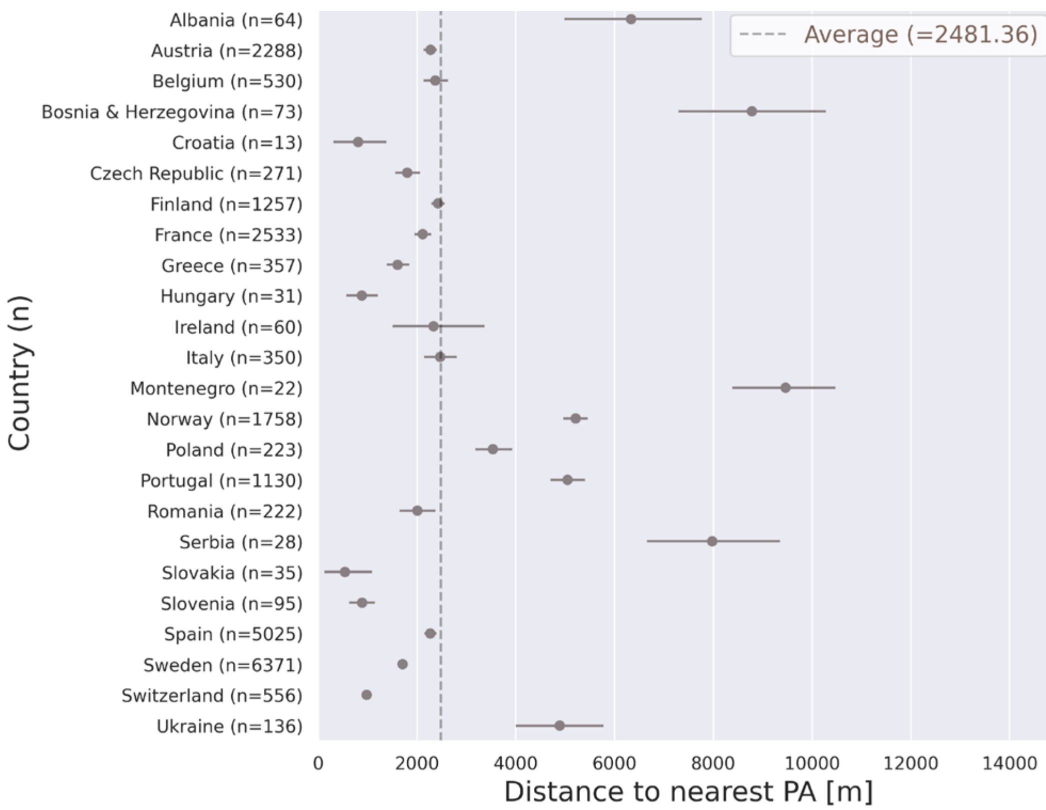

Fig. 2. Distance to nearest PA for each country in the analysed CRM dataset. The dashed line represents the average from all countries. The dot for each country is the average. The line range around the dot represents 5 to 95% confidence intervals. The CRM occurrence count for each country is indicated in parentheses with "n".

A widely used CRM, aluminium, seems to have the lowest mean distance to the nearest PA (Fig. 3). As demand for aluminium is growing while internal production has decreased, there might be interest to increase production within Europe (European Aluminium 2025). However, according to Figure 3, the currently known and reported occurrences seem to be closer to PAs than many other commodities. Lithium, a CRM with use in, e.g., battery production, occurrences have a mean distance little lower than 2 km from the nearest PA.

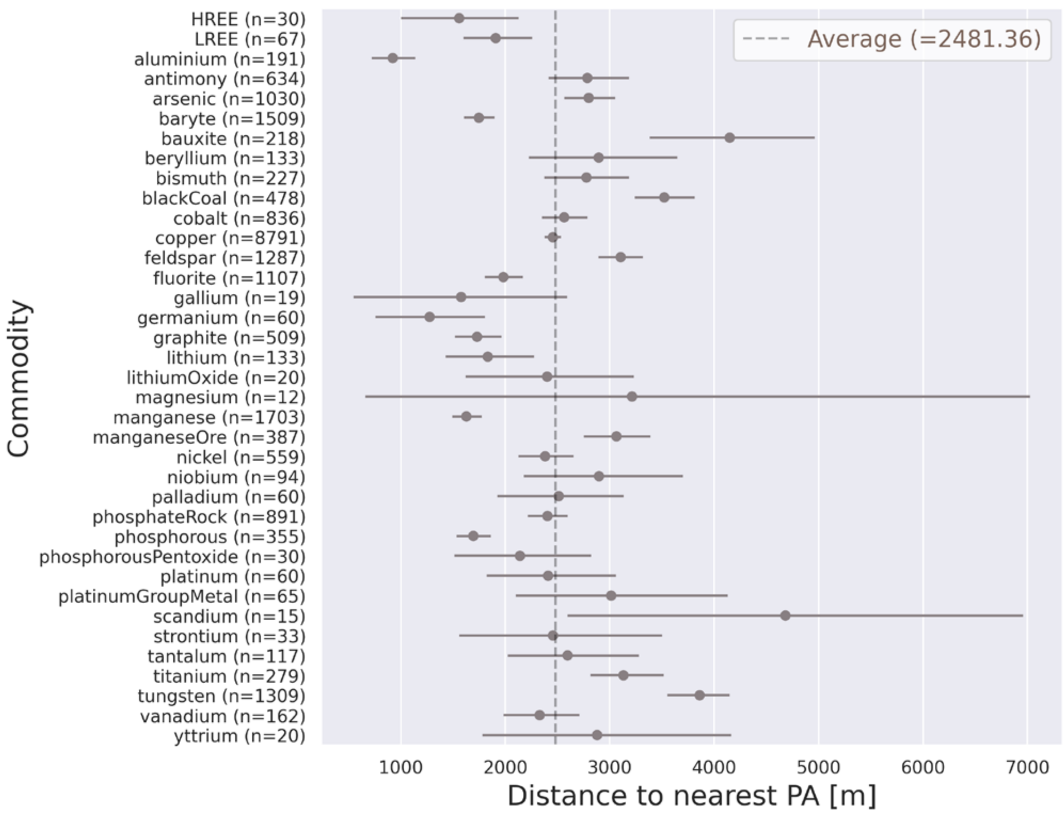

Fig 3. Distance to nearest PA for each commodity in the CRM dataset. For symbol explanations, see Figure 2 caption.

Overall, based on Figures 2 and 3, no country or commodity seems to provide "easy" opportunities for CRM extraction. Rather, coexistence with PAs must be focused on and improved upon to meet the need for CRM extraction within Europe.

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SUSTAINABLE COMMINUTION AND ENRICHMENT PROCESSES OF MINERALS THROUGH THE NEW INNOVATIVE CCC METHOD

by

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There is an increasing demand for innovative and more sustainable techniques for the comminution and beneficiation of critical raw materials. This is a result of the requirements set by the clean transition for the development of less water, energy, and chemicals consuming mineral processing methods. Many methods and chemicals used in the mineral processing are more than 100 years old and have not been originally developed on a sustainable basis. Only now, as the world is in crisis and with the increase in the price of energy, attention has started to be paid more intensively to this.

Such a new and potential innovation is called Continuously Compressing Crushing (CCC), which is based on the free crushing method. In this method, individual particles are passing freely between two rotating press plates until they are broken sequentially via several slow compression cycles. This method reduces the energy consumption per new fracture surface area. The first studies show that during the free crushing in CCC, the formation of overfine particles is reduced, more crystalline and cleaner surfaces are revealed, more liberated particles and microcracks are formed at the natural boundaries of mineral crystals.

The method can be utilised in the more sustainable comminution and beneficiation processes of ore minerals, especially in the dry physical separation, froth flotation, chemical leaching, and bioleaching. Moreover, in the forthcoming process steps consumption of water might decrease dramatically. In addition to the above, one of our research objectives is to analyse the effects of composition and textures on the liberation and classification of minerals during the CCC comminution for different types of ores e.g. iron oxide ore, phosphorate ore, and other metals and minerals containing ores, that are critical for the European Union.

BACKGROUND OF THE PROJECTS

The crushing and grinding of the ore have been carried out with the same kind of equipment solutions throughout the history of enrichment when the goal has been the reduction of size of a material to a certain size class or distribution. In contrast, in industrial processes the real aim should be to produce particle sizes whose processing by separation, dissolution and melting will produce the best ecological and economic results.

Progress has been made in the mining and aggregate industries to reduce emissions, but the access to raw materials is becoming ever more challenging. As we mine deeper for lower-grade materials, the importance of sustainable practices is increasing throughout the entire production chain.

Comminution is essential part of mineral processing designed to separate the components of solid material from each other. The process is very energy intensive, where the loading is arbitrarily directed to particles, like in ball milling that has energy efficiency below 1%.

In addition, one of the main problems is the bad quality of crushing products involving a lot of overfine, undesirable particles. In addition, the fracture surfaces of particles have changed physically and chemically. Thereby making their further processing extremely difficult and limiting application of dry and environment friendly processing.

Accordingly, with the aim of producing high quality particles and with substantially reduced energy consumption, the CCC method has developed a fundamentally new approach to comminution. This paper summarizes the features of the CC crusher, presents the latest research results, and highlights the near future steps.

PRINCIPLES OF CONTINUOUSLY COMPRESSING CRUSHING (CCC)

The starting point of the research is from 2018, when the first version of the crusher was completed and patented (Kuopanportti & Hynynen 2020) in Oulu Mining School, University of Oulu. The patent rights of the technology are now owned by TEVO Oy Machine Workshop. However, the agreement allows the construction of CC crushers for research use at the University of Oulu (UO) and South-Eastern Finland University of Applied Sciences (Xamk).

The basic idea of the method has been to implement the principle of the ideal comminution method as accurately as possible, relying on the theories of fracture mechanics of elastic-plastic materials (e.g., Anderson 2017). Ideal comminution is best achieved when all particles larger than the desired maximum size are slowly broken by free crushing in a wedge-shaped state. Slow compression of a single particle has been shown to be the most energy efficient loading method for several decades (Axelson & Piret 1950, Prentice 1946a,b, Schönert 1979) and Rumpf (1973a,b) has also achieved the best efficiency of refinement with the lowest possible specific energy values. The product of slow load tests thus represents the optimal product of crushing and grinding (Gaudin & Hukki 1944, Hukki 1964).

In this new approach the particles are continuously fed into a double converging space (Fig. 1) which is formed with two lamella conveyors. In free crushing, the particles are compressed slowly and individually such a way that they are not in significant contact with each other and that the broken particles can spread unhindered in the comminution state.

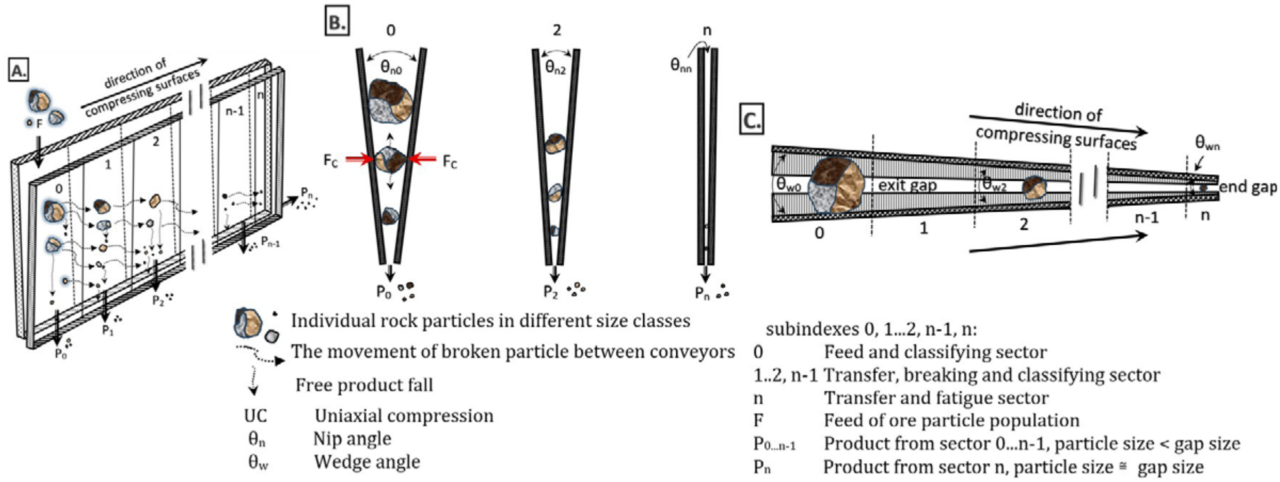

Fig. 1. The operating principle of the new CCC method from lateral side a), front side b) and top c). (Paasovaara et al. 2024)

The CCC method substantially reduces the energy consumption because the uniaxial compression pressure created by the press plates never exceeds the uniaxial compressive strength of a particle. Comparing free crushing method to conventional comminution crushing indicates that energy savings can be significant.

LATEST RESEARCH RESULTS

So far, several crushing cycles have been performed on a few different ore types (graphite bearing schist and metal sulphide ore) using five different crushing methods. Crushing has been performed with 1) a conventional jaw crusher (JAW), 2) a low-load roll crusher (ROLL), 3) a uniaxial compression tests (UC), 4) a free crushing-based laboratory scale continuously compressing crusher (LS-CCC), and 5) pilot scale continuously compressing crusher (PS-CCC). The crushing results of different methods have been compared to determine the grindability behaviour of different ore types under different loads. In the latest studies, the graphite-containing particles processed by different crushing methods have been compared with each other, focusing especially on the appearance (grain size, grain shape, etc.) and enrichment of the independent graphite flakes (Fig. 2b), and the results obtained by different microscopic and chemical methods have been compared in order to find differences or similarities between different size fractions or crushing methods (Fig. 2a). (Paasovaara et al. 2024)

Crushed sulphide ore particles have also been examined e.g., with a stereomicroscope and Field Emission Scanning Electron Microscopy (FE-SEM) to find the differences in mineralogy, texture, and occurrence of microcracking. The most significant results are differences in particle shapes (Fig. 3a,b), and differences in microcracking (Fig. 3c,d).

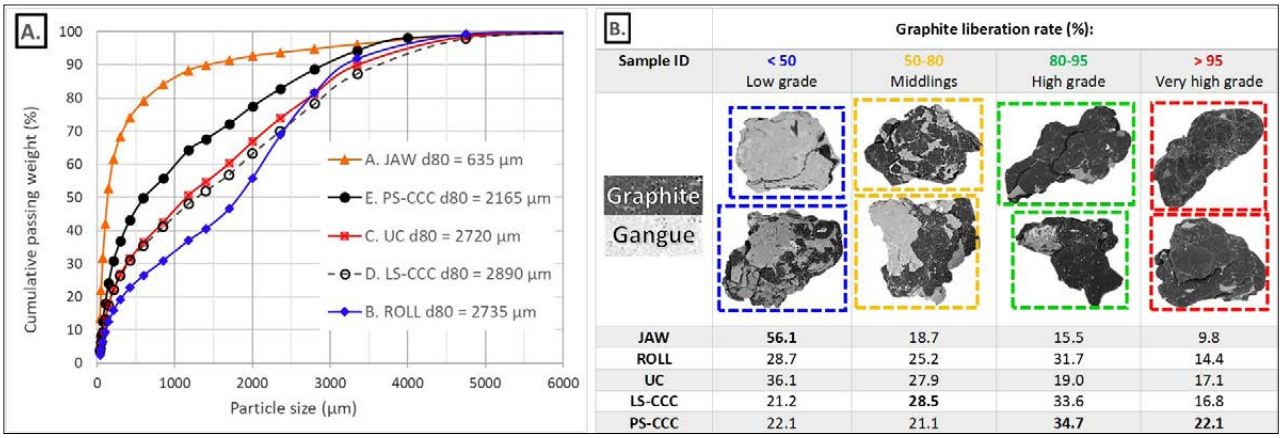

Fig. 2. a) Cumulative percentages of particle size fractions, and b) the result of the liberation examinations of graphite flakes in four different concentration classes. (Paasovaara et al. 2024)

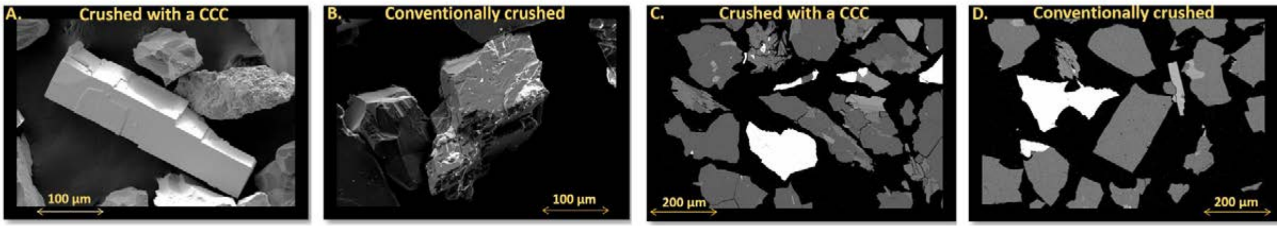

Fig. 3. a) FESEM image of CCC produced mineral crystal surface vs b) conventionally produced mineral surface. c) FESEM image of microcracked particles produced by the CC crusher vs d) conventionally produced particles.

The particles produced with the new CCC method are cleaner and have a narrower particle size distribution making further processing possible in coarser size fractions. In addition, poorer and more challenging raw materials, like ores containing rare earth elements, become possible to beneficiate.

NEAR FUTURE WORK

Currently two projects utilise new innovative CCC method at both laboratory and pilot scale: REMHub project (101177493) and INNOMIN project (A81519). The water fractions resulting from these projects will be studied in more detailed in a MinPhos (354497) project.

The main objectives of the near future research are:

1) to investigate the suitability of more different types of ore minerals and ore textures for the CCC, with a particular focus on metals and minerals, that are critical for the European Union,

2) to investigate the chemical characterisation of mineral samples, i.e., chemical analyses, acid digestions, leaching tests using available technologies at the University of Eastern Finland,

3) to study the effect of CCC on the success of froth flotation and leaching of micro fractured ore minerals,

4) to study the effects of CCC comminuted minerals on water and chemical consumption, and wastewater quality in mineral beneficiation processes, and

5) to improve the efficiency of the crushing process through real-time data collection and visualization, and to create a digital twin that enables process simulation and optimisation.

ACKNOWLEDGEMENTS

This research is part of the "Environmental efficiency for mineral processing through the innovation network – INNOMIN (A81519)" project co-funded by European Union. It is also part of the "Rare earth and magnets hub for a resilient Europe – REMHub" project, funded by the European Union's Horizon Europe research and innovation programme under grant agreement N°101177493. This research is also collaborating with the MinPhos project, funded by the Research Council of Finland (decision no. 354497). This project is also funded by the K.H. Renlund's Foundation.

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A CASE STUDY OF SULPHATE REMOVAL FROM MINE WATER BY NANOFILTRATION – FOCUS ON WATER RECYCLING

by

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INTRODUCTION

Elevated concentrations of sulphate in mine waters are a common environmental challenge. Sulphate levels in mine waters vary widely and have been reported to reach as high as 8–10 g/L (Kinnunen et al. 2018, de la Torre et al. 2011). High sulphate concentrations can limit opportunities for water reuse and pose risks to receiving water bodies. In Finland, regulatory limits for sulphate in mine water discharges were reported to range from 1000 to 4000 mg/L (Runtti et al. 2018). In this study, pilot scale nanofiltration was applied to investigate the potential for producing high quality water (possibly suitable for recycling in mining industry) from various mine waters with relatively high sulphate concentration. Moreover, possibility of mineral and metal recovery from concentrate was investigated. By converting waste streams to value-added commodities, the revenues to offset purification practices on mine sites might be generated. This study is part of an ongoing project and results of NF are based on preliminary investigation, hence, should be considered indicative rather than conclusive.

MATERIALS AND METHODS

Test water

Different mine waters with relatively high sulphate concentrations were tested in this study. Characterisation of the tested mine waters is shown in Table 1.

Table 1. Characterisation of mine waters used in this study.

Parameter (unit)	Value
pH	4.3 – 4.7
Conductivity (µS/cm)	2500 – 4500
Calcium (mg/L)	210 – 480
Magnesium (mg/L)	120 – 140
Sodium (mg/L)	132 –350
Potassium (mg/L)	2 –70
Sulphate (mg/L)	1220 –1500
Chloride (mg/L)	– 583

Experimental set up

Two commercial polyamide thin-film composite nanofiltration (NF) membranes produced by CSM® (NE4040-90 and NE4040-70) were used in this study. Characteristics of used NF membranes are shown in Table 2.

Table 2. Characterisation of NF membranes.

Membrane characteristics	NE4040-90	NE4040-70
Max. operating pressure	4.14 MPa	4.14 MPa
Operating pH range	3.0 – 10.0	2.0 – 11.0
Min. $MgSO_4$ rejection	98%	97%
Max. operating temperature	45°C	45°C

The filtration tests were conducted in cross-flow mode using a pilot module. Prior to NF, mine water went through microfiltration pre-treatment step (0.5 µm). NF was performed at operating pressure of 0.7 – 1.9 MPa, feed flow rate of approx. 1000 L/h and temperature of 21 ± 2°C. Retentate-recycle mode was used for 8 consecutive cycles. Permeate was collected at recovery 30%.

Eight filtration steps were conducted, and concentrations of major and minor elements were determined after each step. The concentrate was further subjected to precipitation and adsorption experiments to remove metals and minerals. To capture the valuable elements in the concentrate, commercially available adsorbent M10 (Aquaminerals, Finland) was used. The adsorption experiments were performed in batch mode. In the batch method, a desired mass of adsorbent was agitated with 50 ml concentrate contained metal ions (overhead shaker) at room temperature for 24 h to reach equilibrium. The effect of adsorbent dose on metals removal was studied by keeping other factors as constant and samples for different dosages were analysed by AAS. Similar experiments were conducted to study the effect of other variables.

Analytical procedures

Concentrations of sulphate, chloride, calcium, magnesium, sodium and potassium were monitored in the feed, permeate and retentate solutions. Sulphate and chloride concentrations were analysed using an ion chromatograph (930 Compact IC Flex; Metrohm) equipped with Metrosep A Supp 5-150/4.0 analytical column and conductivity detector. Sodium bicarbonate/sodium carbonate (3.2 / 1.0 mM) was used as the eluent with flow rate 0.7 mL/min. Column temperature was set at 21 ºC. Calcium, magnesium, potassium and sodium concentrations were measured by means of an atomic absorption spectrometer (contrAA 800; AnalyticJena) with a Xenon short arc lamp as continuous radiator. With its special electrode geometry and physical-technical parameters, a hot spot forms to emit a high radiation intensity across the entire spectral range relevant for AAS of 185-900 nm. During the analysis the position of the hot spot is controlled and adjusted automatically. No warm-up effects due to lamp drift are therefore expected. Any drift of the Xenon short arc lamp is simultaneously removed from the spectra by calculation using correction pixel referencing.

RESULTS AND DISCUSSION

Nanofiltration efficiency for mine water purification

Results of NE4040-90 and NE4040-70 NF membrane performance in terms of rejection of sulphate, chloride, calcium, magnesium, sodium and potassium are shown in Figure 1.

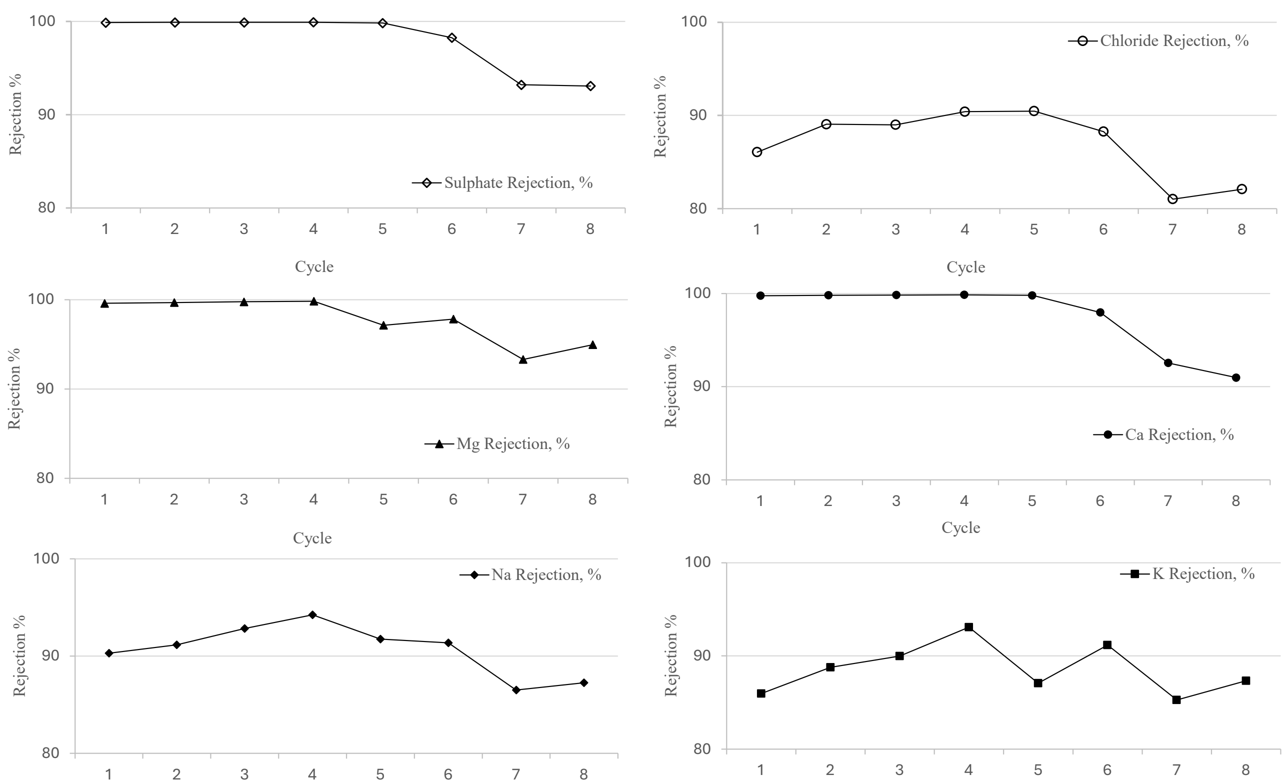

Fig. 1. Rejection of sulphate, chloride, calcium, magnesium, sodium and potassium obtained with NE4040-90 and NE4040-70 NF membranes.

A similar pattern was observed for both tested NF membranes in case of all mine waters. The rejection of sulphate from tested mine waters during five cycles was 99.8 – 99.9%, after which it decreased and reached about 93% at cycle eight. The chloride rejection was 86.1 – 90.5% during first six cycles and then dropped to 81 – 82%. Higher rejection was observed for divalent cations (Ca^{2+} ≥ 98% during first five cycles; Mg^{2+} ≥ 99.6% during first four cycles) compared to monovalent cations (Na^{+} ~ 90.3 – 94.3% during first six cycles; K^{+} ~ 86 – 93.1% during first six cycles). In general, it was observed that after fifths-sixth cycle, rejection of sulphate decreases (chloride, sodium, calcium and magnesium show similar pattern). This could be attributed to the fact that retentate is pumped back to the feed, which significantly increase concentration of ions in it. The results of permeate flux and feed pressure during tested cycles is shown in Figure 2.

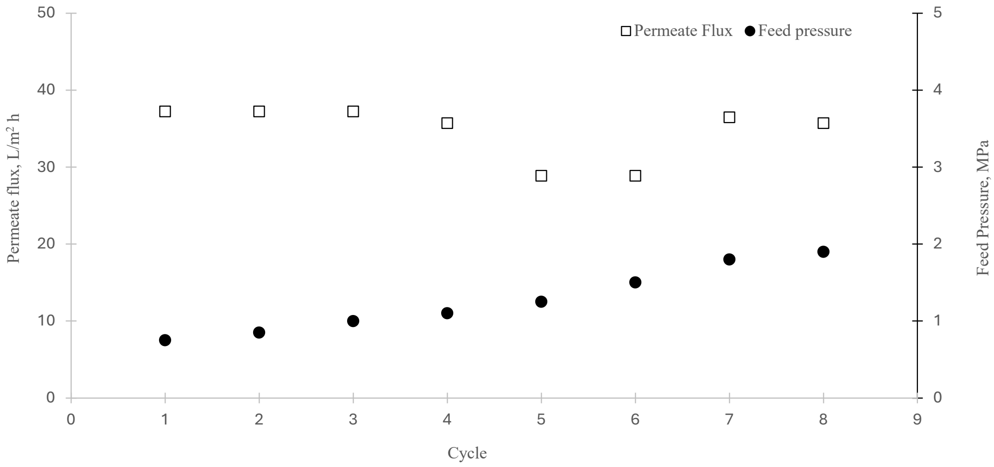

Fig. 2. Permeate flux and feed pressure during tested cycles.

An attempt to keep permeate flux constant during eight cycles was done, which resulted in increase of feed pressure.

Metal capturing and mineral recovery from concentrate

At each concentration step, amounts of purified water, brine, sulphate and pre-concentrated metal ions were evaluated. The NF reject (concentrate) after eight cycles was highly concentrated and contained such ions as chloride (51.4 mg/L), sulphate (9876 mg/L), zinc (133 mg/L), iron (29.8 mg/L), nickel (64.8 mg/L), sodium (757 mg/L), magnesium (1370 mg/L), calcium (454 mg/L), manganese (258 mg/L), potassium (102 mg/L) and aluminium (100 mg/L).

The concentrate was further subjected to precipitation and adsorption experiments to remove metals and minerals. At first step, zinc, nickel, manganese, copper, and cobalt were removed from concentrates via adsorption. The adsorbent dose varied from 1 to 10 g/L, with 3 g/L found to be optimal for zinc, copper, and cobalt removal within 3 h. Removal rates in the range 92 – 99% were observed for all metals. Manganese and nickel required minimum 8h to reach removal rates higher than 92%. At second stage, sulphate present in concentrates that were recovered as gypsum with slaked lime. Further reduction of sulphate concentration was reached by ettringite precipitation with aluminium hydroxide. For concentrate after the 8^{th} step, recovery rate for sulphate was up to 84%, i.e. residual concentration for sulphate 1500 mg/L. Since no significant amounts of harmful elements were captured by gypsum or ettringite, the recovered materials have potential in construction sector as expansive admixtures and composite binders.

CONCLUSIONS

The results of this study are based on preliminary investigations and should be considered indicative rather than conclusive. Nanofiltration demonstrated high efficiency in sulphate removal, achieving 99.8–99.9% rejection during the first five cycles. Both tested membranes (NE4040-90 and NE4040-70) showed similar performance for all tested mine waters. These findings suggest that nanofiltration is a promising method for sulphate removal from mine waters and their potential recycling. Moreover, materials recovered from concentrate have potential applications in the construction sector as expansive admixtures and composite binders.

ACKNOWLEDGMENTS

This study was conducted in frame of AWE-project (Arctic Water Excellence) co-funded by the European Union, Pohjois-Savo Regional Council, South Savo Regional Council, Regional Council of Kainuu and Council of Oulu Region.

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THE AWE – ARCTIC WATER EXCELLENCE PROJECT: STRENGTHENING INNOVATION BASED ON REGIONAL SPEARHEADS IN THE WATER SECTOR AND PROFILED COOPERATION IN THE EASTERN AND NORTHERN FINLAND

by

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Water plays a vital role in mining operations, supporting activities such as drilling, mineral processing, and dust suppression. Although the mining sector accounts for a relatively small share of global water use (Meißner 2021), it is often the largest water consumer at the local level (Norgate & Lovel 2004). In addition to high water consumption, mining generates substantial volumes of wastewater and is a major contributor to the contamination of surface and groundwater near mine sites (Pyrbot et al. 2019). Beyond environmental concerns, water management also presents significant financial challenges. Approximately 10% of capital expenditures in mining are allocated to water management and treatment (Dennis & Dennis 2017, IFC 2021).

Mine water management presents unique challenges due to the dynamic nature of mining operations, which exhibit continuous temporal and spatial evolution. This complexity necessitates ongoing updates throughout the mine's lifecycle and beyond, extending beyond the immediate boundaries of the mining site (Kunz & Moran 2014).

Managing mine water requires an understanding of water interactions and contamination risks. Contaminants such as metals, metalloids, salts, and organic compounds originate from ore composition and processing methods, with sulphide mines posing higher environmental risks due to acid mine drainage (AMD) (Kauppila et al. 2011). The complexities of mine water management underscore the necessity for more consistent and comprehensive approaches to assist mining companies in identifying both risks and opportunities associated with water resource management.

To mitigate environmental risks, advanced tools integrating real-time monitoring, mathematical modelling, and predictive process controls are essential for maintaining water balance, preventing floods, and ensuring sustainable water use throughout the life of a mine (Julien et al. 2005). Proper classification and treatment of wastewater help minimise contamination risks and operational costs. Effective management relies on reliable and well-designed monitoring systems to ensure recycled water meets necessary quality standards, optimising both environmental protection and economic efficiency. To support these efforts, implementing a comprehensive water balance management system is fundamental. Such a system enables efficient tracking, treatment, and reuse of water resources throughout the mining operation.

Water expertise has been identified as a common area of strength for Eastern and Northern Finland. The AWE project (Arctic Water Excellence) aims to strengthen coordinated regional specialization in the water sector and profiled cooperation in the Eastern and Northern Finland. The project implements the choices of the common smart specialization strategy for the region (clean technologies and low-carbon solutions, ICT and digitalization, innovative technologies and production processes), in which the region has been identified as having diverse expertise. The choices of the common strategy create the basis for new supra-provincial cooperation, which the AWE project will concretely implement.

The goal of the AWE project is to contribute to the development of new technologies and their piloting and implementation, especially in water-intensive industry and the water works in cooperation with research institutes, SMEs and industry. The activity aims to promote the formation of new innovations and business in the sector, thus supporting growth and competitiveness of SMEs operating in the sector.

AWE project combines scientific excellence of four regions in Eastern and Northern Finland (Fig. 1). In terms of the smart specialization strategy of Northern Savo, the AWE project focuses specifically on the key theme of a smart water system, implementing its objectives in practice in cooperation with SMEs and industry. The project also supports the implementation of the Water priority of the Kuopio City Ecosystem Agreement. Kainuu region is well known for high quality expertise in measurement technology and currently three mining companies operates in Sotkamo municipality. Kainuu thus provides excellent site for demonstrating novel technologies for industrial water treatment and monitoring. The University of Oulu is an international science university that creates new knowledge, well-being and innovations for the future through research and education. University is a cornerstone of Northern Ostrobothnia region innovation ecosystem together

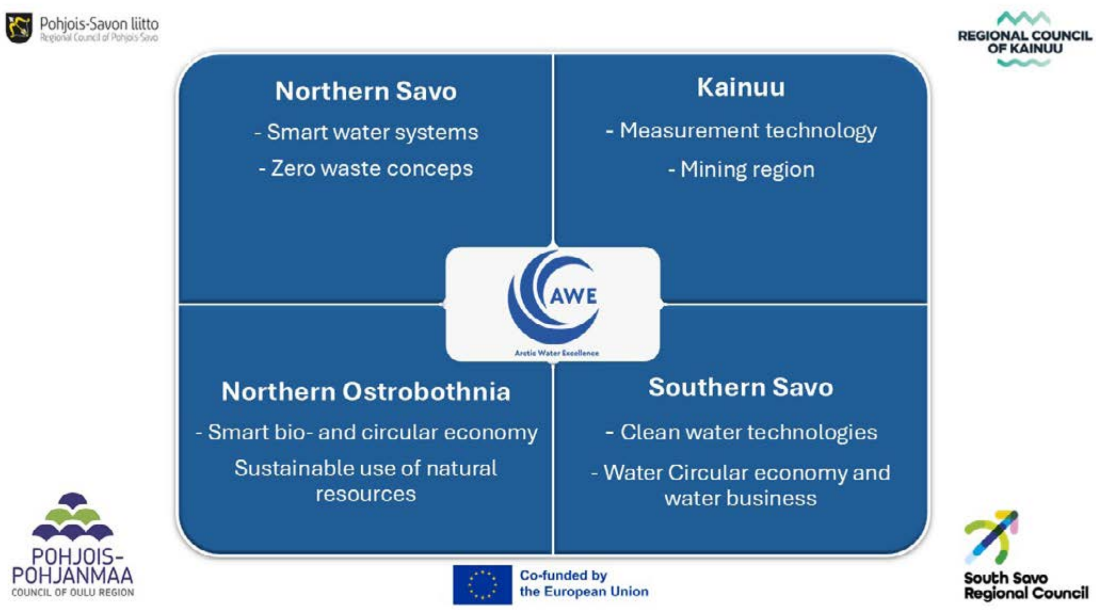

Fig. 1. Schematic illustration of over-regional co-operation in AWE project.

with other research organisations like VTT. One of the key topics of Oulu region innovation excellence is smart bioeconomy and novel circular economy solutions. Southern Savo has international excellence in water research, specializing in water purification and water technology, as well as expertise and training in environmental technology. South-Eastern Finland University of Applied Sciences, in collaboration with LUT University, is implementing research excellence in themes like monitoring of municipal wastewater and new technologies for the removal of harmful substances.

The project's tasks will be implemented in broad, over-regional cooperation by a total of eight research organizations, while significantly strengthening national networking in the water sector and the further development of regional clusters of expertise and their expertise centres in accordance with the goals of smart specialisation.

Savonia University of Applied Sciences is one of the largest and most diverse universities of applied sciences in Finland, operating in the North Savo region with campuses in Kuopio, Varkaus, and Iisalmi. Water safety is one of Savonia's six key research areas. In the AWE project, Savonia acts as the main coordinator, responsible for project management and administration, and is also actively involved in one of the project's four research work packages: Smart Water Management Methods for Industry. This involvement is supported by Savonia's strong piloting capabilities, both in the field and in the laboratory, particularly in water treatment processes and monitoring technologies. These strengths are directly applied in field-based research and development activities in collaboration with other project partners.

The Geological Survey of Finland (GTK) produces impartial research and services in support of decision-making in industry, academia, and wider society to accelerate the transition to sustainable and carbon-neutral world. GTK's research serves the needs of the mining and minerals industries, scientists and policy- makers, and it also benefits the society through the decreased environmental footprint of mining. GTK coordinates the WP2 and develops smart environmental monitoring for mining industry through digitalization.

University of Oulu is a multidisciplinary university located in the north of Finland. **The Measurement Technology Unit (MITY)** is an external research unit and located in Kajaani. The unit has knowledge and skills at high international level in the fields of analytical chemistry and bioanalytics with a focus on development of monitoring technology based on chemical sensors, biosensors and optical spectroscopy. MITY develops new measurement solutions for sulphate removal pilot in WP 2., rapid microbe detection methods and heavy metal monitoring solutions in WP 4. At the **Fiber and Particle Engineering Research Unit** in Oulu, the aim is to develop lignin-derived bioadsorbents. Two approaches are being studied: (1) modification and isolation of wood lignin during delignification to enable the attachment of functional groups, and (2) hydrothermal treatment of technical lignin grades, such as hydrolysis lignin, to optimize their structural properties through carbonization. The performance of the resulting bioadsorbents is evaluated for the removal of cationic and anionic components using both model waters and industrial effluents.

Finnish Institute for Health and Welfare (THL) is a governmental research and expert institute. Department of Public Health is one of the leading expertise organizations of Europe in the field of environmental health. One of the most important spheres of activities in the department is water research with a special emphasis on microbes causing waterborne diseases and the harmful impacts of chemicals in water. THL has modern research facilities (BSL2) and skillful personnel in microbiology.

Kajaani University of Applied Sciences (KAMK) is developing methods to improve sulfate and heavy metal removal from mining waters and studies selective recovery of metals.

The Department of Separation Science at LUT University has built strong expertise over the years in designing selective materials for metal recovery from mining waters, and this knowledge is actively utilized in the AWE project.

South-Eastern Finland University of Applied Sciences (XAMK), in collaboration with LUT University, is working in WP3: Circular Economy of municipal waters. Key themes are developing monitoring of municipal wastewater and new technologies for the removal of harmful substances. Demonstrations of stormwater management will be also done in AWE project.

VTT Technical Research Centre of Finland Ltd contributes to AWE both with technology development and supporting the creation of new businesses based on water expertise. VTT is among others developing a new method for sulphate monitoring. Moreover, VTT has analysed companies' currents needs and challenges and facilitates the creation of joint offering (services, technology) matching markets needs and the consortium expertise.

CASE EXAMPLE

AWE project develops a real-time measurement method for detection of heavy metals. Electrochemical sensor technology offers excellent sensitivity and specificity for water sample measurements. The measurement can be optimized for use with a handheld measuring device or with remote equipment, allowing water quality to be measured at regular intervals or even continuously.

The project is developing a user-friendly measurement solution for measuring cadmium concentration. Cadmium is harmful even at low concentrations, so sufficient sensitivity is required from the electrochemical measurement method. For this reason, the measurement method is being developed to the ppb level. The solution is a portable hand-held device (Fig. 2a) and disposable strip. Data is transferred to mobile app and it is easy to use even without laboratory skills.

a) b)

Fig. 2. Small hand-held measurement device for measuring cadmium a) and measurement camber of real time measurement device for manganese b). (Fig. 2. by Adrina Ferancova).

Manganese is reactive in industrial processes and even if it does not actively participate in the process, it can affect, for example, the consumption of chemicals. Electrochemical sensors make it possible to monitor manganese concentration effectively, even in real time. This makes it easier to optimize the industrial process and the recycling and reuse of materials, thus reducing waste and saving resources. Pilot stand-alone instrument will be built and tested during the project for manganese measurements. Figure 2b shows the developed measurement solutions.

The global market for heavy metal measurement is increasing and there is a need in the market for new measurement solutions that would be available for, for example, mine effluent monitoring, industrial process monitoring or for private consumers, for example, well water quality monitoring.

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DEVELOPMENT OF ENHANCED RESEARCH AND TECHNICAL CAPACITY AT THE GEOLOGICAL SURVEY OF ESTONIA

by

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The EGT-TWINN project aims to improve the research and technical capacity of the Geological Survey of Estonia (EGT) in order to accelerate Estonia's transition from fossil fuels to green energy. The project will promote the development of multidisciplinary geological research and innovation in Estonia and enable the enhancement of scientific excellence of EGT staff and cooperation with experts from leading international research institutions. One of the project's priorities is to support EGT's younger researchers to improve multidisciplinary geological research and focus areas in Estonia.

The EGT-TWINN project has received funding from the Horizon Europe HORIZON-WIDERA-2021-ACCESS-03 call. The capacity building will be mainly focussed on developing state-of-the-art geological, geochemical and geophysical survey skills, data management workflows, and subsurface modelling capability for exploration and geological resource assessment of European critical raw materials and geothermal energy as a potential green energy source for Estonia in future. The EGT geological capacity enhancement will be implemented via delivery of specialised training programmes provided by three leading geological surveys in Europe – the Geological Survey of Finland (GTK), the British Geological Survey (UKRI/BGS) and the Geological Survey of Denmark (GEUS). A further partner is the Oulu Mining School of the University of Oulu (UOULU), which provides a unique state-of-the-art platform for mining-related research and education. In addition, a range of joint activities such as scientific conferences and exchanges will be also arranged. The project will contribute to the development of multidisciplinary research and innovation in geological studies in Estonia and enables EGT to enhance the scientific excellence of its personnel and to collaborate with experts from leading international research institutions. One of the project priorities is to support early-career researchers at EGT who will gain state-of-the-art experience in the geology fields crucial to Estonia. Furthermore, project aims to enhance the dissemination and utilisation of geoscience information, to leverage EGT's expertise in research administration, encompassing project management, financial analysis, and legal matters, and to strengthen EGT's capacity to secure research funding at the national, EU and international levels.

The development activities are going to be implemented in five separate work packages (Fig. 1). The overall objective of the Work Package 1 is to guarantee a smooth day-to-day running of the project for the entire consortium and sound management of all project-related administrative, financial and legal matters. This activity includes, for example, smooth collaboration possibilities between the project partners, organisation of the main project and semi-annual progress meetings, project interim technical review meeting, and make sure that project management structures are properly set up and running well.

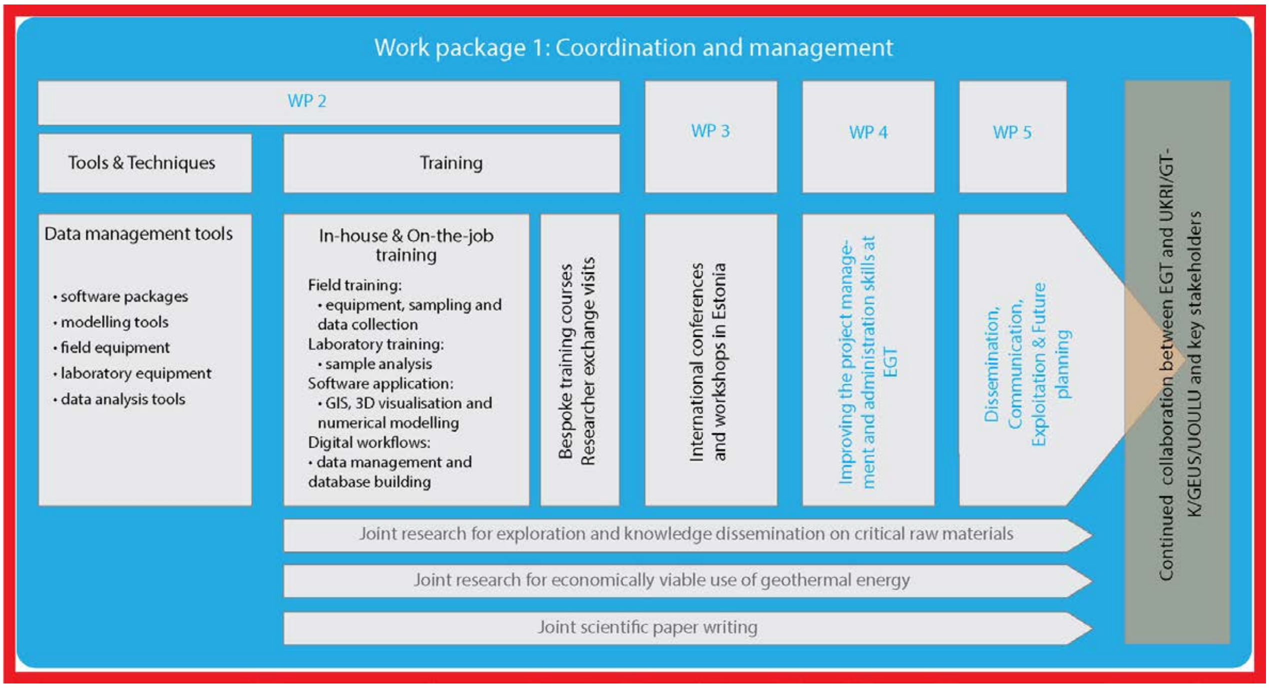

Fig. 1. Organisation of the EGT-TWINN Project into 5 Work Packages.

The Work Package 2 is the most comprehensive EGT-TWINN project work package which is dedicated to strengthening the geological research capacity of EGT. This WP contains seven tasks and 30 actions of which 23 actions were accomplished already in 2024. The specific tasks tackled in WP2 during the first two-year period were:

T2.1 "Assessment of skills, capacity and data management at EGT"
T2.2 "Transition from 2D mapping to state-of-the-art 3D model building practices
T2.3 "Implementing advanced geological surveying techniques"
T2.4 "Geological skills training"
T2.5 "Advanced exploration and valorisation methods of critical raw materials"
T2.6 "Enhancing expertise in geochemical and geophysical studies"
T2.7 "Strengthening knowledge base in geothermal energy studies".

These actions were participated by 41 EGT research staff members – geologists, GIS specialists and database managers which accounts for 82% of the total research staff at EGT in years 2023–2024.

The Work Package 3 focuses on organising international conferences, and so far, two of them were carried out in 2024. The conference "Urban geochemical baseline surveys in Estonia" was organised on September 10, 2024 in Tallinn and this conference had presentations both from experts in Estonia as well as from GTK, BGS and City of Helsinki. The conference program included several presentations focused on soil geochemistry studies, urban geochemical mapping, relevant data handling, and linkages between the soil geochemistry and human health. The topic of second conference was "The conference of exploration and exploitation of critical raw materials (CRM conference)" that was held in Tallinn on October 7–8, 2024. It was very successful event and addressed the critical aspects of exploring and exploiting critical raw materials in northern Europe, with a particular focus on the Baltic States. The event covered the entire CRM value chain – from geology and innovative exploration techniques to processing and environmental, social, and governance considerations. The third conference will be held in 10-12 June 2025 in Tallinn, Estonia with the topic "Geothermal Opportunities for the Baltics". The topic of the fourth conference will be SLE, SLO and Green Mining Concepts and it will be on 16th September 2025.

The main aim of the EGT-TWINN project Work Package 4 is to improve the EGT staff competence in various fields of EU level project management, including financial and legal management, as well as dissemination and exploitation of the results. This will be done by organising several workshops covering topics such as practical project management, project legal and agreement issues, project financial management, and project communication, dissemination and exploitation.

The focus areas in Work Package 5 are the development of the EGT-TWINN communication and dissemination strategy, design of the project logo and the other visual identity elements, the project website and social media channels as well as raising awareness of the general public on the project dissemination events and activities. All of them are available on the web page of the project: https://egt-twinn.voog.com/en.

All the EGT-TWINN project activities during three years period will raise attractiveness of EGT for early-career researchers as a research-oriented geological survey, strengthen networks between EGT and the other project partner organisations and foster communication with the public and policy makers on Earth Science topics towards implementing the green energy transition in Estonia.

OPPORTUNITIES AND CHALLENGES OF ADAPTING INNOVATIONS IN THE MINING INDUSTRY

by

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The Arctic Water Excellence (AWE) project promotes cooperation in Eastern and Northern Finland related to technological innovations in water management. Funded by the European Regional Development Fund, Cohesion Fund and European Social Fund, the project brings together technology developers and research organisations. In addition to advancing technological development the target is to create common competitive offerings on optimised water management process chains for the mining industry, thereby supporting international growth. Mining technology providers are often small companies who, on their own, may lack the capacity or credibility to deliver holistic solutions that meet the complex needs of large mining operations.

METHODOLOGY

The work started with simultaneous analyses of complementary capabilities of the consortium and the market needs. The primary data collection method was in-depth semi-structured interviews. The interviews were conducted both with technology developers (n=6) and with mine companies operating in northern Finland (n=5). Technology developers discussed their products, services, current state, and growth goals, while mining companies shared their needs and openness to new innovations. The product and services of the technology developers cover mining reagents, lignin, on-line monitoring and material recovery. One focal aspect was selective recovery of metals from sides streams and discharge, thereby also ultimately contributing to the resilience issue of critical raw materials (CRMs). Based on the interviews an ecosystem map was created showing the innovation ecosystem. Innovation ecosystems are diverse networks of actors who work together to develop new ideas, products or services which address shared goals (Orlik 2022). (Fig. 1).

Secondary data collection method used in this research was common company and research organisation workshops. Initial co-offerings were drafted during a co-innovation workshop, and mining companies validated the relevance and value of these drafts.

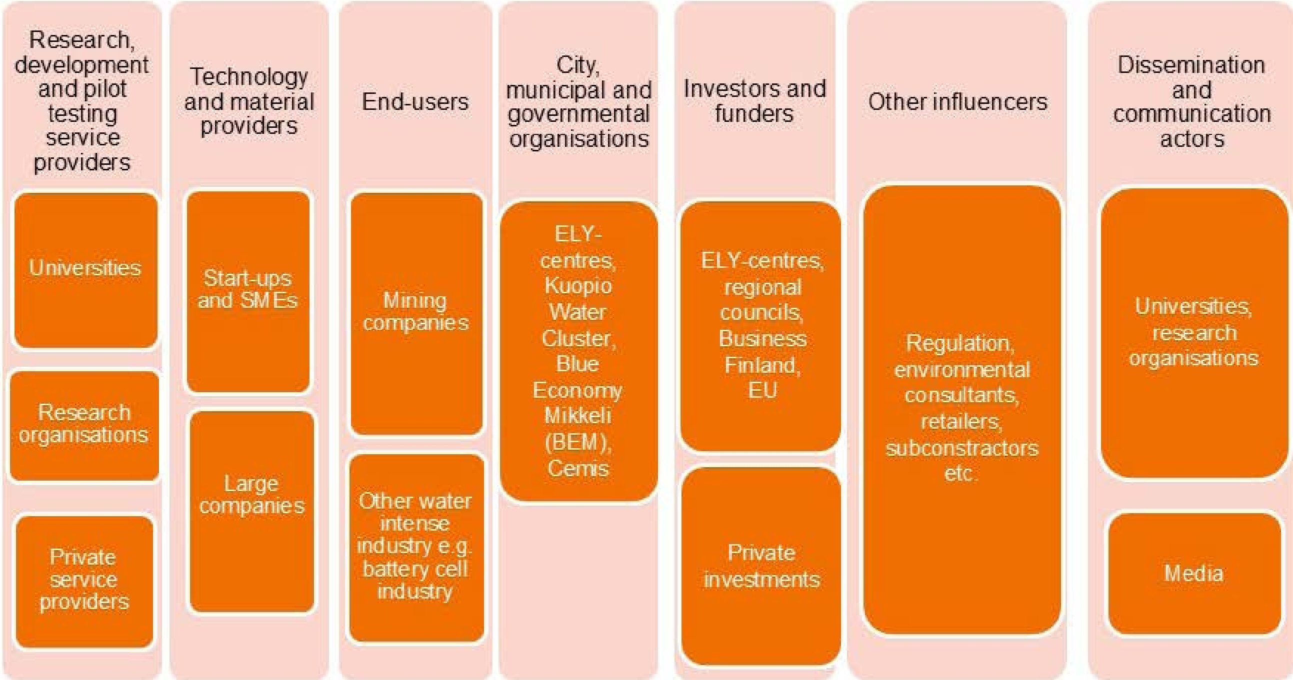

Fig. 1. Innovation ecosystem map.

RESULTS AND DISCUSSION

A major part of the development work in the consortium targets new innovations which would enable recovery of valuable substances from the process residues and water flows with higher selectivity. Such solutions are seen crucial for increased resilience of Finland and Europe and emphasised lately given the political turmoil.

However, technology developers identified several barriers in the endeavour to roll out new innovations on the market. One major barrier is the caution among mining companies to invest in new technological solutions without proven references. This leads to a vicious circle, where technology developers are stuck with market ready solutions, but without references, markets are not easily accessible.

Online monitoring of discharge helps improve situational awareness and facilitates better links between operational actions and discharge quality. However, the demand for online monitoring is limited due to environmental regulations that require or approves only standardized (offline) measurements. Large water volumes and high environmental risks in case of a water treatment process failure exert social pressure on technology developers and mining companies. While mining companies are interested in new technological innovations, they are cautious about adopting them. Changes in one process can lead to modifications required in downstream processes, increasing the cost and complexity of implementing new technologies. Additionally, environmental permits are specific to certain processing chains, and fundamental changes might necessitate reapplication. As a result, operating mines may be hesitant to invest in significant alterations.

Environmental consultants were seen to play a key role with regards to the decision-making process for investments in mining water technologies. Thereby, for new innovations to be acknowledged already in the planning phase, such parties make an important part of the innovation ecosystem and should be involved in the innovation process, alongside regional and national environmental regulatory agencies.

Research centres offering piloting facilities are valuable cooperators for technology developers providing realistic testing and demonstration environments for their innovations. In addition, academic publication and dissemination activities support internationalisation endeavours.

Bottom-up development of innovative joint offerings is an important first step in addressing mining companies' water challenges in a holistic manner. However, simultaneous dialogue with representatives from the client sector is crucial to ensure that technological development aligns with the actual needs of the industry. In this context, an information intermediary plays a vital role by facilitating the flow of information—starting with the identification of technology needs, sourcing potential solutions, and enabling effective technology matching.

Orchestration of an innovation ecosystem is essential to ensure the realisation of the value for the ecosystem members. Because ecosystems are characterised by the presence of stakeholders who make active contributions to the ecosystem offering without relying on formal, one-to-one supplier contracts to coordinate their activities, achieving a value creating outcome requires careful orchestration to inspire appropriate actions in ways consistent with the ecosystem vision (Autio 2021). Centralised orchestration supports required agility and close collaboration within the innovation ecosystem, which is typically limited by already set financial conditions and research and development plans.

ACKNOWLEDGEMENT

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RARE EARTH AND MAGNETS HUB (REMHUB): THE ROLE OF UOULU TOWARDS SUSTAINABLE EU REE SUPPLY AND CLEAN ENERGY TRANSITION

by

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The demand for critical materials, such as Rare Earth Elements (REEs), has seen unprecedented growth as the world transitions towards cleaner energy and sustainable practices. These 17 metals are indispensable for modern technology sectors, including renewable energy systems (wind turbines, solar panels), electronics (smartphones, laptops, displays), electric vehicles (EV motors, batteries), and environmental technologies, which serve as the backbone of numerous high-performance products and processes (De Boer & Lammertsma 2013). However, the accessibility of economically viable REE deposits is limited, posing significant challenges to their supply chain resilience.

Despite their name, REEs are relatively abundant in the Earth's crust; however, economically recoverable deposits are rare and often concentrated in a few geographic locations, resulting in the highest supply risk in the critical raw material list of the EU. Key REEs such as dysprosium (Dy), terbium (Tb), europium (Eu), neodymium (Nd), and yttrium (Y) have been classified as critical materials whose supply chain disruption poses threats to technologies essential for the EU's strategic energy transition. Supply and demand projections for critical REEs such as Nd, praseodymium (Pr), and Dy indicate a growing supply shortfall from 2020 to 2050 (Wang et al. 2024) underscoring the urgent need for new mining investments, advanced recycling technologies, and alternative materials development.

This work outlines the REMHub project's aims, with particular focus on the University of Oulu's (UOULU) multidisciplinary capabilities and strategic contributions to REMHub.

Three research units at UOULU are strategically engaged in complementary initiatives across the entire REE value chain, as illustrated in Figure 1:

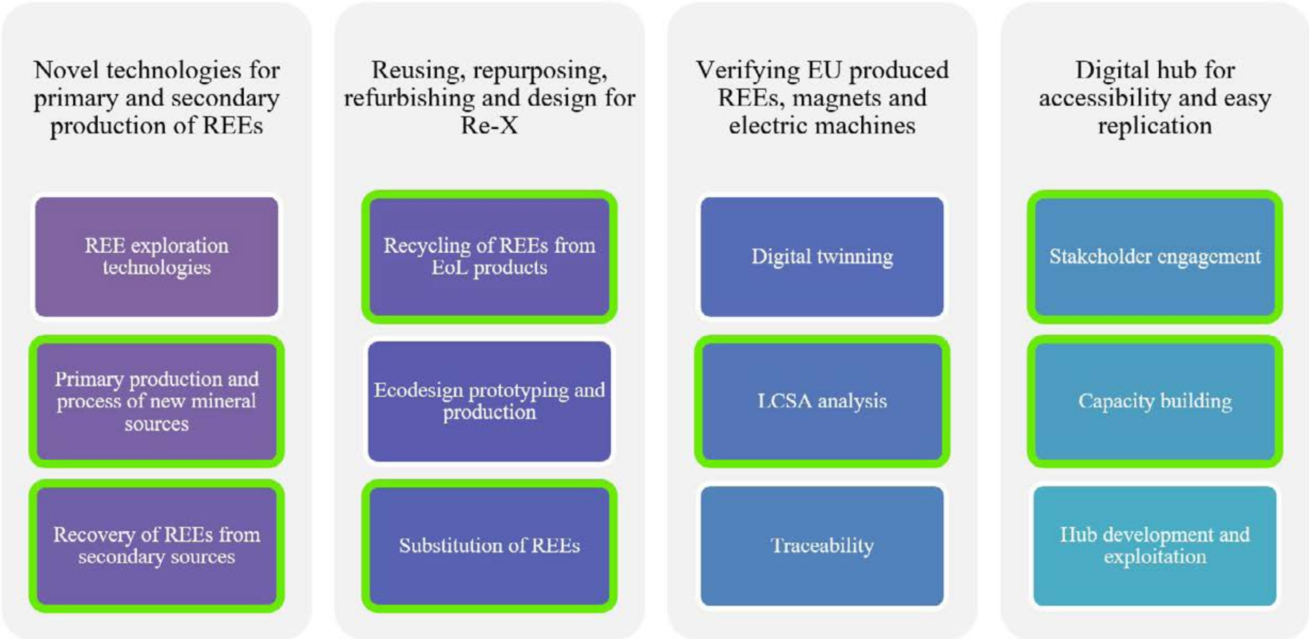

Fig. 1. REMHub project methodology showing integrated approach to European REE supply chain resilience, with the University of Oulu contributions highlighted (green boxes).

Environmental and Chemical Engineering (ECE) focuses on innovating REE refining and separation technologies from primary sources using ion-exchange-assisted hybrid-membrane separation technology. The unit advances Light Rare Earth Element (LREE) substitution research and conducts comprehensive sustainability assessments throughout the REE value chain, applying Life Cycle Sustainability Assessment (LCSA) methodologies to evaluate environmental, economic, and social impacts.

Oulu Mining School (OMS) develops novel processing technologies for primary REE production, including continuously compressing and crushing (CCC) systems for efficient REE ore processing, advanced froth flotation techniques using non-toxic collectors combined with membrane technology, and optimized chemical leaching processes. These technologies target both traditional minerals and non-traditional REE-bearing minerals. The innovative processing equipment developed at UOULU is showcased in Figure 2, featuring the state-of-the-art CCC system for ore crushing and the advanced flotation cell technology that enables more efficient REE recovery from primary sources.

Industrial Engineering and Management (IEM) concentrates on stakeholder engagement strategies, quality assurance frameworks, risk management protocols, Key Performance Indicators (KPIs) development, monitoring strategies, and capacity building initiatives. The unit contributes significantly to the development and implementation of the Innovation Hub, ensuring effective knowledge transfer and technology commercialisation pathways.

The integrated approach in REMHub aims to revolutionize the extraction and recovery of Rare Earth Elements (REEs) by targeting three critical streams: primary sources, industrial side streams, and End-of-Life (EoL) products. By developing innovative technologies and methodologies, REMHub seeks to valorise these streams, ensuring optimized resource utilisation and sustainability. The extracted and purified REEs are then channeled into a novel technology for the sustainable and efficient production of permanent magnets, essential for advancing renewable energy technologies. REMHub addresses immediate REE supply security challenges

Fig. 2. Novel processing technologies developed by Oulu Mining School: continuously compressing and crushing (CCC) system (left) and advanced flotation cell (right) for efficient REE ore processing.

by advancing cutting-edge technologies and sustainable practices while establishing a resilient European critical materials ecosystem. The project significantly contributes to the clean energy transition, reinforcing Europe's technological sovereignty and environmental sustainability in the global shift towards renewable energy technologies.

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