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EU SuperCluster Lapland Geoconference – October 30–31, 2023, Hotel Santa Claus, Rovaniemi, Finland

Abstracts

Vesa Nykänen, Nick Cook and Juha Kaija (eds)

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

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The EU SuperCluster Lapland Geoconference brings together representatives from academia, research institutions and industry to discuss important issues related to critical raw materials within the European Union. The SuperCluster Geoconference included 28 talks and 21 poster presentations covering topics related to innovative mineral exploration, earth observation in exploration and mining, environmental, social and governance in exploration and mining, critical raw materials supply, and new frontiers for exploration. The compilation of the extended abstracts of the oral and poster presentations given in the EU SuperCluster Lapland Geoconference forms this proceedings publication of the Geological Survey of Finland.

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

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INTRODUCTION

The European Union is increasingly and heavily reliant on a limited number of countries as its primary sources for raw materials, particularly critical raw materials vital for strategic sectors like e-mobility, battery production, and renewable energy. Europe has a genuine opportunity to achieve self-sufficiency, resilience, sustainability, and responsible sourcing of critical minerals from its domestic reserves thanks to its geological characteristics and abundant mineral resources.

Nevertheless, many critical raw materials are not found in distinct mineral deposits but are rather extracted as by-products, often in conjunction with primary commodity mining operations. Transitioning to a multi-element approach in mining necessitates a fundamental shift in exploration practices. Exploration efforts must now adopt a more holistic perspective that considers mineral systems in an integrated manner. Additionally, there is a pressing need to pioneer innovative exploration methodologies and data analysis tools to increase the likelihood of discovering new sources of critical raw materials essential for the European Union's economic stability.

The European Union key funding programmes for research and innovation, Horizon 2020 and Horizon Europe support many projects organisations within the member states and beyond. We invited these projects to present their current research findings to each other and discuss about the potential of using these innovative methods in mineral exploration and mining operations.

Twenty-three EU-funded projects focused on raw materials (EIS, AGEMERA, CIRAN, CRM-geothermal, EGT-TWINN, ENICON, EXCEED, GoldenEye, GREENPEG, m4mining, MaDiTraCe, MinExTarget, mine.io, MultiMiner, NetHelix, ROBOMINERS, S34I, SEEMS DEEP, ScaVanger, SEMACRET, START, TRIDENT and VECTOR), in collaboration with the University of Queensland (Australia), joined forces to organise a 1.5-day clustering event titled the "European Union SuperCluster Lapland Geoconference." This event was conducted on October 30 and 31, 2023, in Rovaniemi, Finland.

The primary objective of the SuperCluster event was to convene a diverse spectrum of stakeholders, including representatives from the European Commission, EU projects, and other initiatives in the raw materials sector, as well as regional authorities, industrial leaders, exploration companies, and other interested parties. The aim was to foster discussions and facilitate the exchange of ideas pertaining to the current technological challenges and key topics within the raw materials sector.

The presentations were divided into five sessions with topics related to innovative mineral exploration, earth observation in exploration and mining, environmental, social and governance in exploration and mining, critical raw materials supply, and new frontiers for exploration. In these sessions, we had 28 oral presentations, and 21 poster presentations were also presented during the meeting. The session included presenters answering questions from the audience. After the sessions, the meeting ended with a panel discussion where we had four participants representing the mining industry, consultants, academia and research institutions.

Participating projects funded by the Horizon Europe (HE), Horizon 2020 (H2020), EIT Raw Materials (EIT RM) and European Regional Development Fund (ERDF):

EIS – Exploration Information System (HE)

AGEMERA – Agile Exploration and Geo-modelling for European Critical Raw materials (HE)

CIRAN – CrItical RAw materials extraction in enviroNmentally protected areas (HE)

CRM-geothermal – Raw materials from geothermal fluids: occurrence, enrichment, extraction (HE)

EGT-TWINN – Enhancing research capacity at the Geological Survey of Estonia to accelerate the country's transition to green energy (HE)

ENICON – Sustainable processing of Europe's low-grade sulphidic and lateritic nickel/cobalt ores and tailings into battery-grade metals (HE)

EXCEED – Cost-effective, sustainable and responsible extraction routes for recovering distinct critical metals and industrial minerals as by-products from key European hard-rock lithium projects (HE)

GoldenEye – Earth observation and Earth GNSS data acquisition and processing platform for safe, sustainable and cost-efficient mining operations (H2020)

GREENPEG – New Exploration Tools for European Pegmatite Green-Tech Resources (H2020)

m4mining – Multi-scale, Multi-sensor Mapping and dynamic Monitoring for sustainable extraction and safe closure in Mining environments (HE)

MaDiTraCe – Material and digital traceability for the certification of critical raw materials (HE)

MinExTarget – Enhanced Use of Heavy Mineral Chemistry in Exploration Targeting (EIT RM)

mine.io – A Holistic Digital Mine 4.0 Ecosystem (HE)

MultiMiner – Multi-Source and Multi-Scale Earth Observation and Novel Machine Learning Methods for Mineral Exploration and Mine Site Monitoring (HE)

NetHelix – Intelligent digital toolbox towards more sustainable and safer extraction of mineral resources (HE)

ROBOMINERS – Resilient Bio-inspired Modular Robotic Miners(HE)

S34I – Secure and Sustainable Supply of Raw Materials for EU Industry (HE)

ScaVanger – Sustainable Supply of Scandium for the EU Industries from Liquid Residues from Chloride-Based TiO2 Plants (EIT RM)

SEEMS DEEP – Seismic and Electromagnetic Methods for Deep Mineral Exploration (ERA-MIN)

SEMACRET – Sustainable exploration for orthomagmatic (critical) raw materials in the EU: Charting the road to the green energy transition (HE)

START – Sustainable Energy Harvesting Systems Based on Innovative Mine Waste Recycling (HE)

TRIDENT – Technology based impact assessment tool foR sustaInable, transparent Deep sEa miNing exploraTion and exploitation (HE)

VECTOR - Vectors to Accessible Critical Raw Material Resources in Sedimentary Basins (HE)

New Regional Circular-Economy Promoting Co-operation and Bio-Cover Practices in Arctic Mine Tailings (ERDF)

Projects funded from other sources:

BATTRACE – Sustainable Processing and Traceability of Battery Metals, Minerals and Materials (Business Finland)

MaViSkene – Finnish material flow analysis and scenario work on the use of natural resources in support of circular economy agreement (National funding)

Towards a fossil-free society: the mineral economy as a substitute for peat production (Kohti fossiilivapaata yhteiskuntaa: mineraalitalous turvetuotannon korvaajana/AKKE funding)

Organising committee

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AGEMERA: FUELLING A GREENER ECONOMY VIA INNOVATIVE MINERAL EXPLORATION

by

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The evolving environmental, economic, and societal requisites within the EU necessitate the development of innovative methods for mineral exploration that align with a transition towards a low-carbon and digital economy. AGEMERA, a three-year Horizon Europe project budgeted at €7.5M (grant agreement N° 101058178), spearheads this initiative by implementing cutting-edge geological and geophysical surveys across approximately 4,700 km^2, encompassing Finland, Poland, Spain, Bosnia-Herzegovina, Bulgaria, Germany, and Zambia (Holma et al. 2022, 2023). AGEMERA aims to map critical raw material (CRM) resources and improve genetic mineral system models for various deposits known to contain CRMs.

Three innovative, non-invasive survey techniques will be showcased during geophysical field trials: passive seismic methods, a multi-sensing drone system integrating magnetic, radiometric, and electromagnetic sensing, and a muographic multidetector density detection system. These novel approaches hold promise for efficient data acquisition and heightened automation, fostering a unique value proposition against traditional geophysical procedures. Still, conventional ground geophysics is also applied.

AGEMERA's geological work encompasses a comprehensive review of selected CRM districts, focusing on their geological, geochemical, and geophysical characteristics and structures involved in mineralisation. The research targets these deposit types: orogenic gold with atypical metal association (e.g., Co), sediment-hosted stratiform copper (e.g., Co), greisen (e.g., Li), karst bauxite (Al), porphyry copper (e.g., PGMs), epithermal gold (e.g., the unknown potential for CRMs), polymetallic veins (e.g., Sb, baryte, Bi, Co, fluorite, W), volcanic-hosted massive sulphide (e.g., Co, In, PGMs), and iron-oxide copper-gold (e.g., Co, REE, P). New geological data are collected by a variety of field research methods. This data, analysed with laboratory studies, yields additional insights into CRMs' distribution, grade, and control. Data also enables computer-based modelling to identify overlooked exploration regions. The final phase enhances or develops new mineral system models for CRM-hosting ore deposits in the selected areas. This information will be vital for present and future project developers to find new ore deposit systems, supporting the sustainability of current mining areas.

AGEMERA assembles twenty partners dedicated to pioneering mineral exploration techniques, fortifying the sustainable supply of CRMs, and advancing the EU's strategic autonomy, thereby fuelling innovation for a greener economy.

REFERENCES

Holma, M., Korteniemi, J., Casini, G., Saura, E., Šumanovac, F., Kapuralić, J. & Tornos, F. 2022. Agile Exploration and Geo-modelling for European Critical Raw Materials – Introduction to the AGEMERA project. Institute of Seismology, University of Helsinki, Report S-72, 51–54.

Holma, M., Peytcheva, I., Šumanovac, F., Tornos, F., Nyambe, I. & Joutsenvaara, J. 2023. Horizon Europe project AGEMERA: Combining novel methodologies for agile exploration and geomodelling of critical raw materials deposits. Proceedings of the Geological Society of Finland, Vol. 3, Abstracts of the 1st GeoDays 14th–17th March 2023, Helsinki, Finland. University of Helsinki, p. 43.

GEOCHEMICAL MATERIAL FINGERPRINTING FOR TRACKING RAW MATERIAL FLOWS IN COMPLEX SUPPLY CHAINS

by

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The energy transition towards renewable and fossil-free energy and the electrification of transportation will require a substantial amount of technology metals and materials, such as nickel (Ni), cobalt (Co), lithium (Li) and graphite for rechargeable batteries used in electronic devices and electric vehicles or Rare Earth Elements (REEs), neodymium (Nd) in particular, for permanent magnets use in wind turbines. However, their supply chains, from mining to manufacturing and end use, are complex, involving several countries and actors, and come with local and global social, environmental, and economic impacts. Therefore, consumers, and downstream manufacturing companies are increasingly interested in the sustainability and responsibility of the raw materials value chain of their end-products. New regulations are also pushing towards more transparency and will likely dictate global developments regarding raw materials sourcing. The buyers of minerals and metals are thus under pressure to be able to prove the provenance of their raw materials (e.g., from which mines or countries are they extracted). This is even more important for technology materials as any sustainability or responsibility issues in their supply chain would be in contradiction with the environmental objectives they are supposed to contribute to.

This talk will present the material fingerprinting (MFP) approach developed in the HE project MaDiTraCe which is based on material geochemical properties (trace elements, isotopes) and artificial tagging approaches (Fig. 1), as an independent tool to support traceability and certification schemes. As the intrinsic geological and elemental characteristics of a material cannot be falsified, the method has unique potential as a stand-alone traceability technology, or as a complementary verification method for the information provided by the producers to the digital traceability solutions by allowing to control, verify or certify materials declared origin.

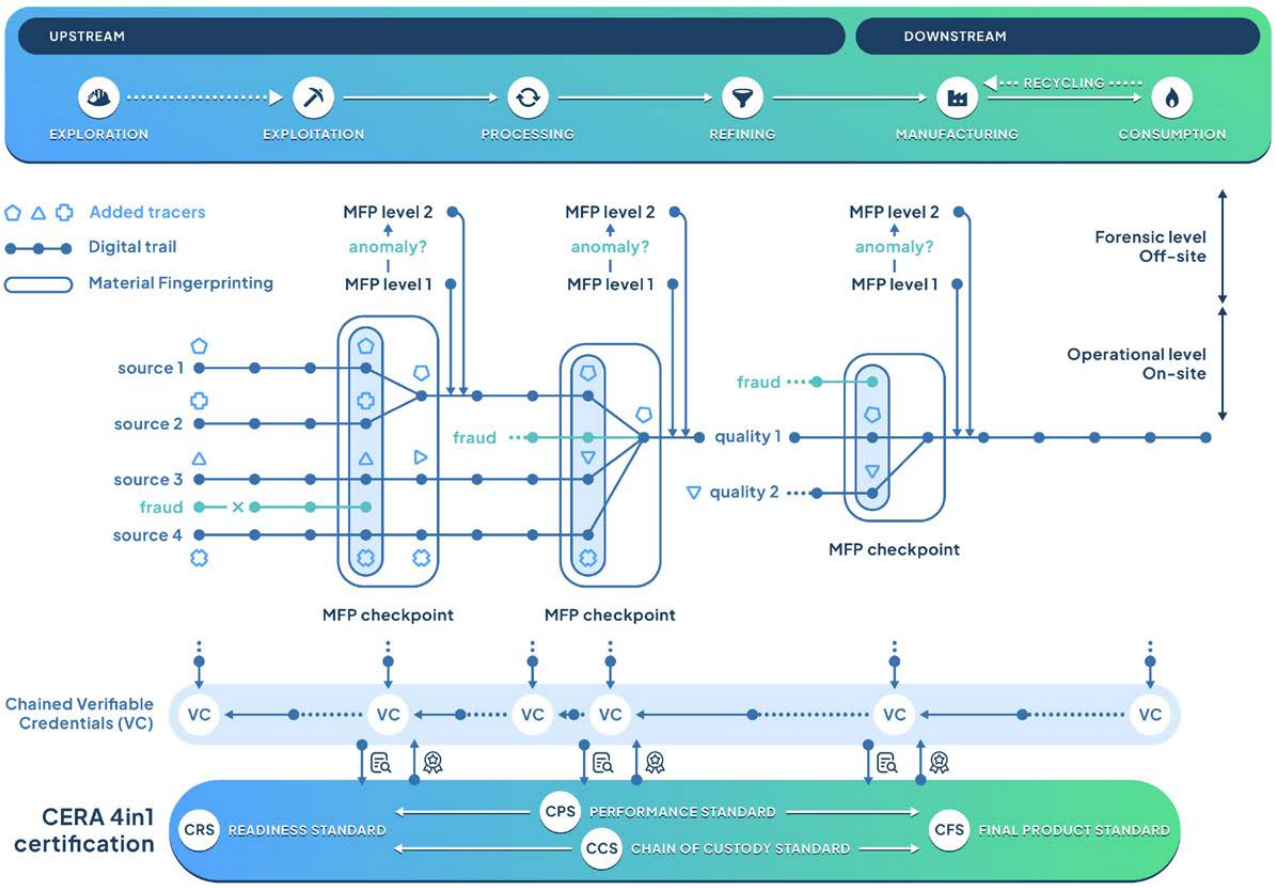

Fig. 1. Conceptual scheme of the MaDiTraCe approach to CRM traceability and certification.

A MINERAL SYSTEMS APPROACH ON CRITICAL RAW MATERIAL DEPOSITS IN EUROPE

by

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INTRODUCTION

The green transition to a larger share of renewable energy that the modern society is facing requires access to metals and minerals for new infrastructure and technological development, and there is high uncertainty over their long-term availability. These supply risks have already been shown following Russia's invasion of Ukraine, and in the role of Critical Raw Materials (CRMs) in the 2020-to-present semi-conductor crisis. In the 2023 EU report on CRMs (Grohol & Veeh 2023) it is stated that OECD forecast a doubled raw material demand from 79 billion tonnes today to 167 billion tonnes in 2060. Global competition for resources is expected as the dependence of CRMs replace today's dependence on oil. Their responsible sourcing cannot be guaranteed without domestic supplies or production within the EU. To secure future (preferably local) resources, it is important to understand the formation, distribution, and deportment of CRM-bearing deposits.

Although the CRM potential in Europe is high, many deposit types are challenging exploration targets due to their exotic, atypical nature that require specialised exploration strategies. Several deposit types with CRM-potential, such as rare earths-cobalt-bearing iron oxide-Cu-Au (IOCG) systems, lithium-tin-tantalum-tungsten bearing granite/pegmatite-related systems and cobalt-bearing volcanogenic massive sulfide (VMS) systems, have not been placed into a proper metallogenetic and tectonic framework. Mineral exploration relies on immature conceptual ore genetic models for many types of CRM-bearing deposits. Despite the significant amount of data generated by current research and exploration, there is a lack of synthesis and integration with large-scale geological models. This presents a long-term risk to realise domestic and European supply chains as the lead-time from initial discoveries to code-compliant mineral reserves is typically over 10 years.

MINERAL SYSTEM MODELLING

The mineral systems approach was initially introduced by Wyborn et al. (1994) within the context of the Australian Proterozoic mineral system. This approach is designed to encompass all geological factors that govern the genesis and preservation of mineral deposits, underscoring the significance of comprehending underlying processes (Fig. 1). Ore deposits typically arise as a result of large-scale geological processes and systems that exhibit spatial concentration at specific locations. The prediction of these locations necessitates a comprehensive understanding of the entire system. This approach integrates all available geological and geophysical data to construct a conceptual model elucidating the overarching formation of ore deposits and their relationship to the regional geological framework. Consequently, the investigation of a mineral system entails the examination of multiple scales, encompassing both deposit-level and continental crustal scales. The formation of ore deposits is contingent upon a myriad of constituents and processes, all of which necessitate in-depth study:

- Source of fluids and ligands
- Source of metals and other components
- Migration pathways and fluid conduits (inflow and outflow zones)
- Thermal gradients
- Source of energy to transport fluid and metals
- Mechanical and structural focusing mechanism at trap site
- Chemical and/or physical trapping mechanism causing precipitation

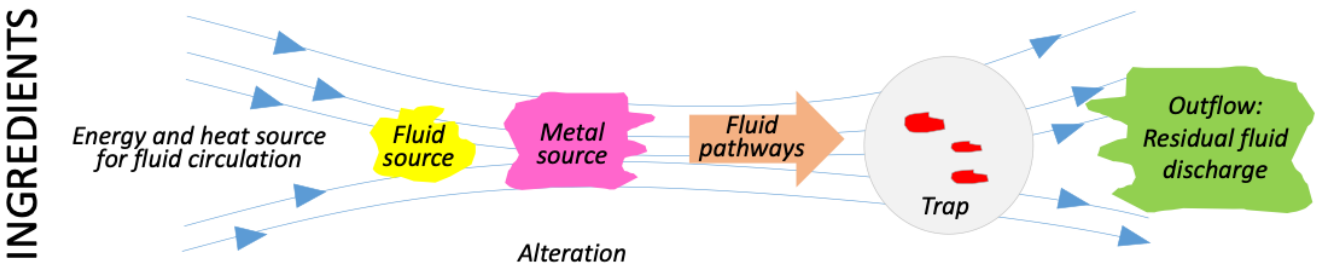

Fig. 1. Mineral systems model (from Knox-Robinson & Wyborn 1997).

A fundamental distinction between ore deposit modeling and the development of models rooted in the mineral system approach lies in the latter's consideration of ore deposits as transient outcomes resulting from geological processes that operate on significantly larger temporal and Earth-system scales in comparison to the highly localised and sporadic concentration of metals within a relatively limited portion of the Earth's crust (McCuaig et al. 2010, Hagemann et al. 2016, and references therein). Stated differently, the intervening processes leading to the genesis of a mineral deposit exert their influence over a much broader expanse of the Earth's crust than the deposit itself. The significance of this comprehensive approach in the realm of mineral exploration is exemplified by the secular occurrences of various types of mineral deposits throughout Earth's history.

CRITICAL RAW MATERIAL MINERAL SYSTEMS IN EUROPE

In the course of the EIS project selected CRM-bearing mineral systems all over Europe are investigated. The main focus of the project comprises cobalt minerals in VMS systems, lithium-tin-tantalum-tungsten minerals in granite/pegmatite-related systems, and rare earths-cobalt minerals in IOCG systems.

Volcanogenic massive sulfide deposits (VMS) constitute significant sources of base metals, particularly in Europe, where they manifest as multiple clusters of substantial economic importance, exemplified by regions like the Skellefte-Bergslagen districts in the Arctic and the Iberian Pyrite Belt (IPB). Among these deposits, the stockwork zones exhibit notable enrichment in cobalt (Co), leading to the current evaluation of their substantial potential, as observed in the Tharsis and Sotiel mines within the IPB. Remarkably, a growing cohort of VMS deposits, sharing characteristics with the Besshi type, such as Tisová (Czechia), Klingenthal (Germany), or Touro (NW Spain), hosts even higher Co concentrations and promises to emerge as a substantial Co resource for Europe in the near future. Nevertheless, on a global scale, limited information is available regarding the Co potential within VMS systems. Historically, Co has been considered a by-product, either included in sulfide concentrates or discarded. Its economic grades, typically ranging from 0.05 to 0.1 wt%, are notably lower than those of base metals (0.05-0.1 wt%), often leading to its oversight in systems primarily dominated by Cu, Zn, or Pb. Preliminary findings indicate that Co-bearing phases are enriched, not exclusively but predominantly, within massive sulfides associated with primitive igneous rocks and dark shale. Additionally, these phases exhibit localised enrichment along later structural traps, suggesting that sheared VMS systems can harbour zones of high-grade ore.

Lithium deposits across the globe are categorised into various genetic types, with the hard rock type (e.g., granitic pegmatite) and the brine type receiving significant attention for extraction purposes. Lithium can also accumulate in sedimentary basins through the alteration and weathering of adjacent granites. Highly altered granitic rocks or pegmatites can lead to greisen-type lithium mineralisation, concurrently concentrating other incompatible elements such as tin, tungsten, rubidium, and cesium, with zinnwaldite being the primary lithium mineral. Lithium-cesium-tantalum (LCT) pegmatites represent a compositionally defined subgroup of granitic pegmatites known to host lithium and various other commodities, including tin, tantalum, niobium, and scandium. While most lithium exploration primarily focuses on high-grade pegmatites, recent research suggests that granite/pegmatite-related systems can generate extensive alteration haloes with elevated concentrations, potentially yielding mineable deposits that were previously unrecognised. These intrusion-related systems rarely co-occur with lithium-tin-tantalum and tungsten deposits, which typically form as independent ore bodies within the same mineral system. Often, a single deposit contains only one or two of the aforementioned commodities, despite their association with similar peraluminous intrusions.

A diverse assemblage of loosely defined deposits is linked to late-orogenic processes during significant European orogenic phases, such as the Variscian and Svecokarelian events. These deposits have been categorised into several ore genetic models based on localised mineral associations, hydrothermal imprints, and structural contexts. These genetic models encompass iron-oxide copper gold (IOCG) and orogenic gold deposits and encompass more broadly defined classes like shear-zone hosted graphite and rare earth element (REE) deposits. Despite their diverse appearances and distinct genetic interpretations, these deposits exhibit several common features that suggest a shared genetic origin. Recent

research further suggests that these deposits formed within similar tectonic and structural settings, with minor variations attributed to differences in fluid and host rock compositions.

ACKNOWLEDGEMENTS

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REFERENCES

Grohol, M. & Veeh, C. 2023. Study on the Critical Raw Materials for the EU 2023 – Final Report. European Commission Report. 158 p. doi:10.2873/725585

Hagemann, S. G., Lisitsin, V. A. & Huston, D. L. 2016. Mineral system analysis: Quo vadis. Ore Geology Reviews 76, 504–522.

Knox-Robinson, C. M. & Wyborn, L. A. I. 1997. Towards a holistic exploration strategy: using geographic information systems as a tool to enhance exploration. Aust. J. Earth Sci. 44, 453–463.

McCuaig, T., Beresford, S. & Hronsky, J. 2010. Translating the mineral systems approach into an effective exploration targeting system. Ore Geology Reviews 38, 128–138.

Wyborn, L. A. I., Heinrich, C. A. & Jaques, A. L. 1994. Australian Proterozoic mineral systems: essential ingredients and mappable criteria. Conference Proceedings 1994 AuslMM Annual Conference, Darwin, August 1994. AusIMM Publ. Ser. 5 (94), 109–115.

EXPLORATION INFORMATION SYSTEM (EIS): OPEN-SOURCE TOOLKIT & QGIS WIZARD FOR MINERAL PREDICTIVE MAPPING

by

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The research described in this extended abstract focused on the design of the Exploration Information System (EIS), specifically on the design of the so-called "EIS Toolkit" and the "EIS QGIS Plugin". EIS intends to provide a combination of the mineral system approach and mineral predictive mapping (MPM) tools in the open-source geographic information system (GIS) software of Quantum GIS (QGIS). We investigated the possibilities of current MPM software used for similar tasks as well as Python libraries that could be used in our own implementation for EIS. A list of required functionalities for the EIS Toolkit was compiled and prioritised for implementation in EIS. We interviewed different types of users of different software available today and carefully studied the MPM workflow they are using. A process document for the development of EIS-related software was designed and tested and can now be found at the GitHub repository of the EIS Toolkit: https://github.com/GispoCoding/eis_toolkit

The design work continued with a series of workshops arranged by GTK, Gispo and Beak focusing on the user interface of existing software and the expected user experience for the planned EIS QGIS Plugin. The EIS QGIS Plugin can be found on GitHub: https://github.com/GispoCoding/eis_qgis_plugin

Both software products – EIS Toolkit and EIS QGIS Plugin – will be published with a free and open-source EUPL 1.2 licence, which is a GPL-compatible copy left licence.

INTRODUCTION

This extended abstract provides an overview of the background, concept and design of the EIS Toolkit and the QGIS EIS Plugin developed in the EIS project. EIS Toolkit is a Python library of functions customised for mineral prospectivity mapping (MPM) and analysis. The QGIS EIS Plugin consists of two parts: The EIS Wizard and the EIS Processing Toolbox. The EIS Wizard is a user interface guiding through different steps of prospectivity analysis and providing the possibility to organise data and track the processing workflow. The EIS Processing Toolbox is the QGIS interface to the EIS Toolkit functions, and it can be used outside the EIS Wizard for building custom prospectivity analysis workflows in QGIS, for instance, with the QGIS model builder.

The main objective of EIS is the development of a GIS (Geographical Information System)-based Exploration Information System (EIS) for predictive mapping of mineral resources. EIS does not have a strict definition, but can be characterised as an environment for performing data analysis and modelling, for managing data and other information, and for representing results in various forms (Yousefi 2019, Yousefi 2021).

In this research, the general structure of the "EIS QGIS Wizard" was developed and main contents of the "EIS Toolkit" and the "EIS Processing Toolbox" were defined and described. The planning of the general structure of "EIS QGIS Wizard" involved both infrastructure and content related questions. A successful wizard-like solution requires creating an organised structure between each workflow step and identifying the possible needs user may have during the workflow. Our goal was to identify and design the components to be included in the wizard and generate a list of tools and functionalities that will be included in it. Only tools with clear roles/uses were included in the wizard design. We also reviewed existing software and explored the possibilities to utilise the tools / plugins already existing in QGIS and elsewhere as open-source code.

The idea of the "EIS Toolkit" is to act as a comprehensive Python library of independent functions relevant for mineral prospectivity analysis. These tasks include mainly predictive mapping and data integration via mathematical modelling, but also some general data processing and analysis. Also, tools for evaluation of the goodness of the models and modelling results will be included for efficient decision making in the identification and prioritisation of exploration targets. "EIS Toolkit" will contain implementations of existing and new algorithms. Emphasis is given to exploring the applicability of modern machine learning methods, such as convolutional neural networks, the use of which in mineral prospectivity modelling is still at its infancy.

The structure of and interfaces to the functions included in the library have been planned so that the functions can be smoothly integrated to other software, such as the "EIS QGIS Wizard". Existing Python libraries have been reviewed and are used to minimise the coding effort. Only functions that are not directly available in other libraries included in the toolkit are implemented.

BACKGROUND

Mineral Predictive Mapping

Predictive modelling of areas favourable for the existence of undiscovered mineral deposits is usually called mineral predictive modelling, mineral prospectivity modelling or mineral potential modelling. Instead of modelling, some researchers

use the term mapping. A more general term to describe this complex multi-stage process is mineral prospectivity analysis. The number of different terms already suggests that there is no universally recognised best way or set of established tools for producing information about where the deposits most likely are.

Mineral systems of any type are connected with specific characteristic geological features, often distinct from the surrounding geology. As these features have certain physical and chemical properties, mineral systems often can be distinguished from the surroundings by integrating spatial geochemical and geophysical information from different sources (vegetation, till or stream sediment samples, airborne or ground geophysical measurements, even satellite-based measurements). Mineral systems are complex, however, and the surrounding geology varies in different places, which makes it difficult to generate universally applicable models for even a certain type of mineral system. The approaches to carry out modelling (integrating data from different sources) include unsupervised and supervised modelling methods. Unsupervised methods are used, when there are not enough training data, i.e., known deposits, in the study area. These approaches require using a priori expert knowledge, i.e., qualitative estimates, on how different geochemical and geophysical quantities are related to the deposit and its surroundings. Supervised methods make use of training data to generate a mathematical model for relating measurement data to the existence of deposits. Both approaches require a lengthy procedure of data processing prior to actual modelling to transform the original measurements into a form that best distinguishes the mineralisation. In machine learning nomenclature this procedure is called feature engineering.

Mineral System Approach

There are certain geological phenomena related to the formation of each type of mineral system that leave a footprint on the deposit location and its surroundings. The mineral system approach in prospectivity analysis means that the geological processes of the entire mineral system over time, instead of just the deposit itself, is carefully considered when selecting and processing the input data in prospectivity analysis. An EIS contains, in addition to prospectivity modelling tools, a library of mineral system components and the related observable features for each type of mineral system to facilitate selection and processing of input data.

METHODS

Software Concept

The tools in the "EIS Toolkit" will be integrated into the "EIS QGIS Wizard", a guided end-to-end implementation with a visual user interface for performing mineral prospectivity analysis. "EIS QGIS Wizard" will be running under the open GIS platform, QGIS, thus bringing the developed methods and tools openly accessible to everyone. In addition to the tools in the "EIS Toolkit", the wizard will include general data exploration, processing, and visualisation tools. The functionality of "EIS QGIS Wizard" can roughly be divided as follows:

- Data pre-processing tools, which will enable transforming primary geoscientific data to synthetic features representing mineralisation processes and/or mineralisation-related/favourable geological features.
- Data analysis tools, which will enable the visualisation and exploratory data analysis of the primary and pre-processed data, as well as testing of geological hypotheses connected with the primary and synthetic features.

- Data integration and modelling tools, which include statistical, analytical and machine learning based data analysis tools for integrating information from different types of input data. The tools can be used, depending on the case, to either generate mineral prospectivity models or to extract from the datasets relevant features related to the mineral deposits. Both supervised and unsupervised machine learning techniques will be included.
- Model testing tools, which are used for testing the prediction capability and/or the success rate of the model. Several tools are included for different use cases.
- Tools for creating visual outputs, which produce maps representing data (input data, refined data and derived data), plots describing obtained results, and models obtained from data analysis/integration. Tools for visualising data and results in spatial frame are important because both the data and the examined phenomenon (i.e., mineral deposit occurrence) are spatial in nature.

The "EIS QGIS Wizard" will be implemented so that additional algorithms or tools can be added later to each section. This allows this project to act as an opening statement for building a complete GIS-based data analysis pipeline for implementation of machine learning methods on geospatial datasets for mineral prospectivity modelling. Because the source codes of the "EIS QGIS Wizard" as well as the "EIS Toolkit" will be distributed openly in GitHub or in a similar software distribution platform, contributions from numerous developers globally are allowed, making the development, maintenance and updating of such a complex system possible.

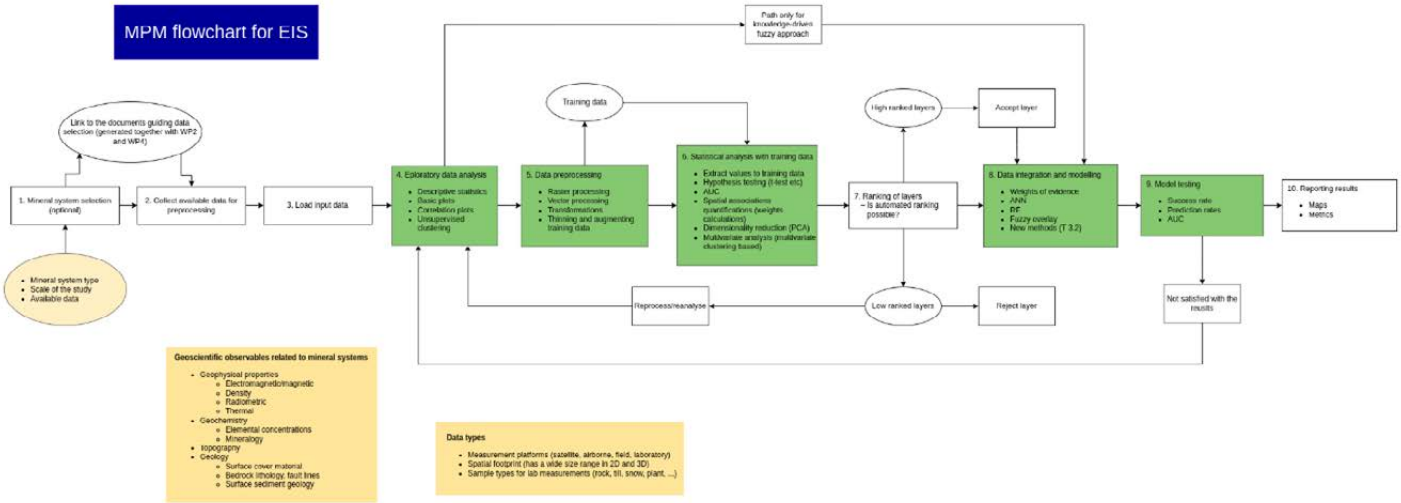

Fig. 1. Mineral predictive mapping (MPM) flowchart for EIS.

EIS Toolkit

The algorithms of EIS Toolkit will be divided into different modules based on their role in mineral prospectivity mapping workflow. These modules group the tools to make the structure of the toolkit intuitive for users.

EIS QGIS Plugin

EIS QGIS Plugin is the graphical user interface (GUI) designed for EIS Toolkit. Because the GUI is created as a QGIS plugin, users won't need any additional software to visualise their data and can leverage many useful features of QGIS.

EIS QGIS Plugin is comprised of two main components: EIS QGIS Wizard and EIS QGIS Processing Algorithms. Initially, EIS QGIS Wizard was supposed to be the only GUI for EIS Toolkit. However, it was later decided that implementing individual tools from the toolkit as QGIS Processing Algorithms would be beneficial to allow users to access the tools without using EIS QGIS Wizard and to leverage the Model Designer feature in QGIS.

An important note to make is that EIS QGIS Plugin does not perform any computations or execute EIS algorithms. All processing will be handled in EIS Toolkit and EIS QGIS Plugin will merely order computations and fetch results.

EIS QGIS Wizard

EIS QGIS Wizard is the primary GUI component of EIS QGIS Plugin. EIS QGIS Wizard will facilitate project management, group related tools and steps and guide more inexperienced users through an MPM workflow.

The clearest and most important way to understand EIS QGIS Wizard is through UI windows. The wizard is planned to have the following windows:

Pre-processing window, which facilitates processing mapable proxies of geological processes from primary/raw geological data.

Exploration window, which shows different methods to explore the selected data. Visualisations and analysis reports will be embedded in the exploration window.

Modelling window, which allows users to select a modelling method of their choice and do final preparations for their model data. This window will likely also involve validation, unless it is decided validation needs its own window.

Settings window, which allows users to set and configure miscellaneous settings, such as EIS Toolkit installation location.

Project management is facilitated by utilising the tree-like, hierarchical structure of layer groups in QGIS. Groups will be automatically created and populated when a project is started and when processing algorithms are run. For simplicity and because it was seen sufficient, an EIS project is coupled with a QGIS project file. All settings, layers and project state are saved in a QGIS project file.

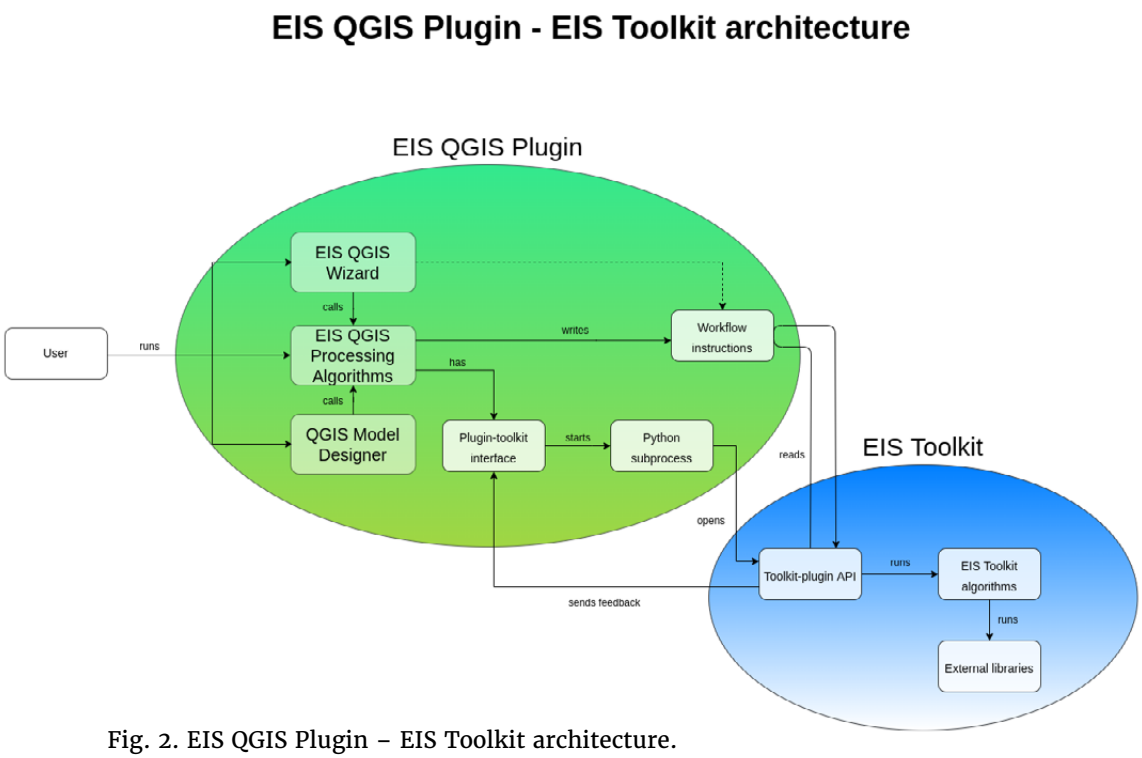

Fig. 2. EIS QGIS Plugin – EIS Toolkit architecture.

The UI of EIS QGIS Wizard will be implemented using PyQt5 Python library, both programmatically and using Qt Designer, a software made specifically to design Qt graphical user interfaces. Most of the design work so far has been carried out in UI design workshops involving programmers and stakeholders, and the initial implementation has been created based on comments by an UI designer, geologists and PyQt programmers.

RESULTS

As multiple organisations take part in the development work for the EIS Toolkit and the QGIS EIS Wizard, a software development process taking this into account had to be agreed upon and documented. With the help of other project partners, Gispo defined the contributing guidelines and documented them into GitHub, which is used to host both the EIS Toolkit Python library and EIS QGIS Plugin. The guidelines instruct with setting up a development environment, how to write functions/code, how to test and finally how to submit new functionality as Pull Requests. After a Pull Request has been submitted it will be reviewed by one or more of the developers of the project.

The two repositories can be found from:

- https://github.com/GispoCoding/eis_toolkit/
- https://github.com/GispoCoding/eis_qgis_plugin

The EIS Toolkit repository has been opened for public access and the EIS QGIS Plugin repository will be made public at a later stage of development.

ACKNOWLEDGEMENTS

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REFERENCES

Yousefi, M., Kreuzer, O. P., Nykänen, V. & Hronsky, J. M. A. 2019. Exploration information systems – A proposal for the future use of GIS in mineral exploration targeting. Ore Geology Reviews 111, 103005. Available at: https://doi.org/10.1016/j.oregeorev.2019.103005. Available at: https://www.sciencedirect.com/science/article/pii/S0169136819301490

Yousefi, M., Kreuzer, O., Nykänen, V. & Hronsky J. 2021. Exploration information systems – A proposal for the future use of GIS in mineral exploration targeting. Ore Geology Reviews 111, 103005. Available at: https://doi.org/10.1016/j.oregeorev.2019.103005

THE MINEXTARGET PROJECT: MINERAL EXPLORATION BY TRACE ELEMENT AND ISOTOPIC ANALYSIS OF HEAVY MINERALS

by

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MINEXTARGET PROJECT AND THE DISCRIMINATORY POWER OF MINERAL COMPOSITIONS

Sedimentary overburden hinders ore exploration by masking the bedrock, but one should not despair, as the study of surficial sediments can lead to a bonanza. Ore exploration methods relying on glacial till chemistry (see McMartin & McClenaghan 2001) have been successfully used to target some of the most significant recent ore discoveries in Canada and the Fennoscandian shield (e.g., Brownscombe et al. 2015). In addition, the indicator mineral approach that monitors the number of heavy minerals or gold nuggets in sedimentary samples (see McClenaghan 2005) is routinely used in the exploration for gold and diamonds (Girard et al. 2021, Malkovets et al. 2016) and gaining popularity in the exploration of other ore types (McClenaghan et al. 2020).

MinExTarget is an EIT RawMaterials supported European Union project that aims for a new ore exploration service that utilises the composition of heavy minerals in sediments for ore exploration targeting. We work to improve methods of indicator mineral separation, automated identification, and compositional analysis, using glacial (Finland), fluvial (Poland and Norway), and marine sediments (Norway) as sample material. Furthermore, we develop multivariate analysis techniques for identifying prospective isotopic, and minor and trace element signatures in heavy mineral grains. So far, pyrite, scheelite, monazite, and cassiterite grains have been studied in detail, and developments are in progress regarding other sulfide and oxide minerals.

Crystallisation conditions affect the substitution of minor and trace elements in the mineral lattice. Hence mineral species – although later eroded from their origin – can have compositions indicative of their genetic origin, e.g., the type of ore they were eroded from. For example, the minor and trace element concentrations in pyrite are distinctive for various ore types (e.g. Gregory et al. 2019), and even capable of discriminating between certain ore subtypes, e.g., orogenic gold deposits with or without base metal enrichment (Raič et al. 2023). Scheelite grains

are also useful as genetic tracers, since their composition is susceptible to the redox conditions of the environment they are formed (Nie et al. 2023). Furthermore, cassiterite trace element contents distinguish between hydrothermal and magmatic crystallisation and track the evolution of hydrothermal fluids (Zhang et al. 2022).

INTRODUCTION TO THE ROMPAS-RAJAPALOT PROTOTYPE TEST

The MinExTarget ore exploration service was prototype tested at Mawson Gold Ltd's exploration area at Peräpohja Belt, northern Finland. The study area includes the epigenetic-hydrothermal Rompas-Rajapalot deposit composed of multiple Au-Co mineralised pipes that are hosted by volcanic and sedimentary supracrustal rocks (Molnár et al. 2017, Ranta et al. 2021). Glacial till with a typical thickness of up to five metres covers the Au-Co-enriched bedrock.

The sample material was collected from the C-horizon or deeper levels of the glacial till. Pyrite, scheelite, and monazite were then separated from the sedimentary fraction and pre-concentrated for heavy minerals using a Knelson concentrator. This process was followed by a newly developed in-house mineral separation method that utilises high-density LST *Fast Float* low-toxicity heavy liquid at high temperatures (90 °C). The produced concentrates were first scanned for indicator minerals with SEM–EDS, and then pyrite and scheelite grains were analysed for minor and trace element composition with LA-ICP-MS.

Two multivariate analysis techniques were utilised to classify the scheelite and pyrite trace element data: principal component analysis (PCA) and self-organising maps (SOM). Both are standard techniques to transform high-dimensional data into a lower-dimensional representation. PCA algorithm reduces the dimensionality by identifying the directions, known as principal components, along which the data varies the most. The first principal component captures the maximum amount of variance in the data, followed by the second, and so on. SOM, in turn, reduces multidimensional data to a two-dimensional map by creating a grid of artificial nodes that are arranged by a process called competitive learning so that nodes with data points most alike are closest to each other. These nodes of the SOM map can be further clustered, e.g., with the K-means algorithm.

SCHEELITE AND PYRITE TRACE ELEMENT ANALYSIS RESULTS

Scheelite was recovered and analysed from most glacial till samples (20 out of 29 samples) in low quantities (<20 grains/sample). Compared to the scheelite grains in the Rompas-Rajapalot deposit, compositions of glacial till scheelite are distinctly Mo-rich and As-poor (Fig. 1a,b). Only five of the 96 scheelite grains analysed – all from samples near the known bedrock Au-Co-occurrences had the chemical character of the Rompas-Rajapalot ore scheelite (Fig. 1a,b).

Pyrite grains, always showing signs of strong oxidation (Fig. 1d), were recovered from eleven till samples near the known bedrock ore occurrences. Even though one sample had hundreds of pyrite grains, typically less than 15 grains per sample were large enough (>50 µm) for compositional analysis with LA-ICP-MS. The pyrite minor and trace element contents were a good match to the pyrite compositions of Rompas-Rajapalot and other orogenic Au deposits. Furthermore, SOM analyses revealed that pyrite grains recovered from glacial till directly above or near the mineralised bedrock had the most ore-like geochemical signature.

DISCUSSION

Ore-type scheelite and pyrite grain compositions were identified from glacial till near the bedrock ores. This indicates that the Au-enriched bedrock generates a mineral compositional signal to the surrounding sediments. This signal can be used to locate yet unknown bedrock ores.

It was easy to classify the scheelite compositions of the glacial till samples due to the distinctiveness of ore-type scheelite compared to the majority of scheelite grains in glacial till (Fig. 1a,b). The geochemistry of most glacial till scheelite grains can be related to relatively oxidising crystallisation conditions. Many of these grains are compositionally closer to scheelites from greisen rather than orogenic Au deposits. Therefore, we suspect that most of the analysed glacial till scheelite grains originate from hydrothermal alteration of granites, while the rare ore-type scheelite grains have crystallised from more reduced, potentially auriferous, fluids.

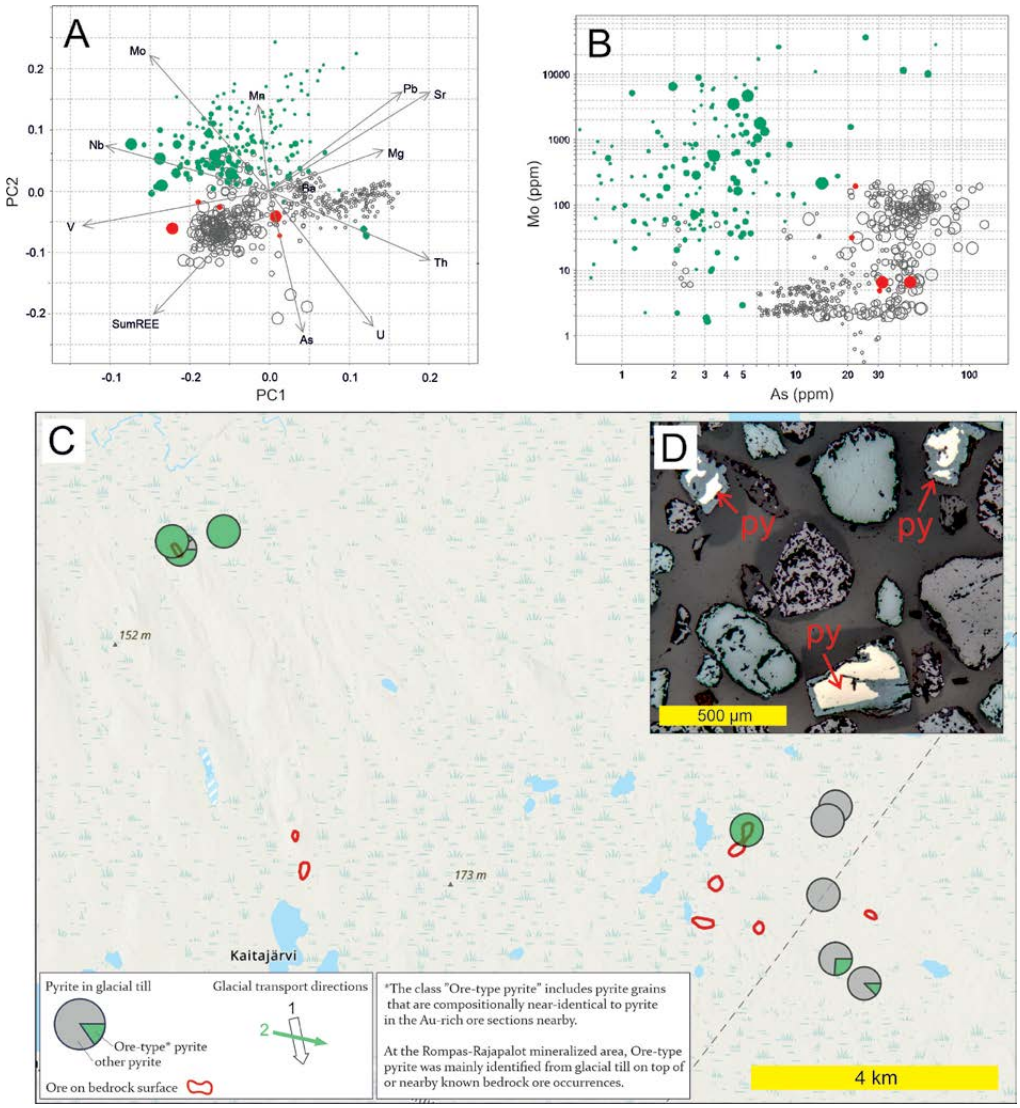

Fig. 1 a, b) The first two principal components (clr-transformed data) and a Mo–As biplot of the scheelite trace element data. Hollow symbols are the Rompas-Rajapalot deposit scheelite compositions and filled symbols are compositions of glacial till scheelite. The five glacial till scheelite grains matching with the Rompas-Rajapalot mineralisation are emphasised with a red color. The symbol size is relative to the REE content. c) A map of the pyrite-bearing glacial till samples and the bedrock surface expressions of the known mineralised pipes at the Rajapalot exploration area. d) A reflected-light image of oxidised pyrite grains (py) in a glacial till sample.

Pyrite grains were recovered only from glacial till in the vicinity of the known Au-Co ore occurrences (Fig. 1c), and almost all glacial till pyrite compositions were comparable to pyrite of the Rompas-Rajapalot Au-Co deposit. These findings resulted in two issues: (i) unlike with scheelite, a compositional range for the non-ore pyrite could not be defined within the study area; and (ii) a straightforward differentiation between the pyrite-bearing glacial till samples was not possible. Anyhow, later analyses revealed that pyrite grains that most resemble auriferous pyrite of the Au-rich units of the Rompas-Rajapalot deposit are distinctively common in glacial till samples taken above the mineralised bedrock (Fig. 1c). This finding suggests that the complete range of pyrite compositions from the Rompas-Rajapalot deposit poorly defines the pyrite geochemical signal related to Au-enrichment and conforms with previous work suggesting multiple hydrothermal events at the Rompas-Rajapalot area (Molnár et al. 2017, Raič et al. 2022). The likelihood of multistage pyrite crystallisation should be considered when defining mineral geochemical vectors to ore.

REFERENCES

Brownscombe, W., Ihlenfeld, C., Coppard, J., Hartshorne, C., Klatt, S., Siikaluoma, J. K. & Herrington, R. J. 2015. The Sakatti Cu-Ni-PGE Sulfide Deposit in Northern Finland. In: Maier, W. D., Lahtinen R. & O'Brien H. (eds) Mineral Deposits of Finland. Amsterdam: Elsevier, 211–252.

Girard, R., Tremblay, J., Néron, A., Longuépée, H. & Makvandi, S. 2021. Automated gold grain counting. Part 2: What a gold grain size and shape can tell! Minerals 11, 379.

Gregory, D. D., Cracknell, M. J., Large, R. R., McGoldrick, P., Kuhn, S., Maslennikov, V. V., Baker, M. J., Fox, N., Belousov, I., Figueroa, M. C., Steadman, J. A., Fabris, A. J. & Lyons, T. W. 2019. Distinguishing ore deposit type and barren sedimentary pyrite using laser ablation-inductively coupled plasma-mass spectrometry trace element data and statistical analysis of large data sets. Economic Geology 114, 771–786.

Malkovets, V. G., Rezvukhin, D. I., Belousova, E. A., Griffin, W. L., Sharygin, I. S., Tretiakova, I. G., Gibsher, A. A., O'Reilly, S. Y., Kuzmin, D. V., Litasov, K. D., Logvinova, A. M., Pokhilenko, N. P. & Sobolev, N. V. 2016. Cr-rich rutile: A powerful tool for diamond exploration. Lithos 265, 304–311.

McClenaghan, M. B. 2005. Indicator mineral methods in mineral exploration. Geochemistry: Exploration, Environment, Analysis 5, 233–245.

McClenaghan, M. B., Ames, D. E. & Cabri, L. J. 2020. Indicator mineral and till geochemical signatures of the Broken Hammer Cu–Ni–PGE–Au deposit, North Range, Sudbury Structure, Ontario, Canada. Geochemistry: Exploration, Environment, Analysis 20, 337–356.

McMartin, I. & McClenaghan, M. B. 2001. Till geochemistry and sampling techniques in glaciated shield terrain: A review. Geological Society Special Publication 185, 19–43.

Molnár, F., O'Brien H., Stein, H. & Cook, N. D. J. 2017. Geochronology of Hydrothermal Processes Leading to the Formation of the Au–U Mineralization at the Rompas Prospect, Peräpohja Belt, Northern Finland: Application of Paired U–Pb Dating of Uraninite and Re–Os Dating of Molybdenite to the Identification of Multiple Hydrothermal Events in a Metamorphic Terrane. Minerals 7, 171.

Nie, L., Wang, F., White, N. C., Zhang, D., Yan, C. & Wang, X. 2023. Scheelite trace element compositions: A robust new tool for mineral exploration, Ore Geology Reviews 155, 105338.

Raič, S., Molnár, F., Cook, N. D. J., O'Brien, H. & Lahaye Y. 2022. Application of lithogeochemical and pyrite trace element data for the determination of vectors to ore in the Raja Au–Co prospect, northern Finland. Solid Earth 13, 271–299.

Raič, S., Molnár, F., O´Brien, H., Cook, N. D. J. & Vasilopoulos, M. 2023. Building geochemical vectors with trace element compositions of sulfides in orogenic gold mineral systems in northern Finland. Journal of Geochemical Exploration 251, 107252.

Ranta, J.-P., Cook, N. D. J. & Gilbricht, S. 2021. SEM-based automated mineralogy (SEM-AM) and unsupervised machine learning studying the textural setting and elemental association of gold in the Rajapalot Au-Co area, northern Finland. Bulletin of the Geological Society of Finland 93, 129–154.

Zhang, J., Shao, Y., Liu, Z. & Chen K. 2022. Sphalerite as a record of metallogenic information using multivariate statistical analysis: Constraints from trace element geochemistry, Journal of Geochemical Exploration 232, 106883.

EXPLORING NYF-TYPE PEGMATITE DEPOSITS IN TYSFJORD, NORWAY, THROUGH THE IMPLEMENTATION OF GROUND GEOPHYSICS

by

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INTRODUCTION

GREENPEG (2020–2024) is an EU-funded project under Horizon 2020 aimed at developing comprehensive exploration toolsets to identify lithium-rich pegmatites and high purity quartz deposits using multiple approaches. The primary objective of the project is to establish an economically viable and sustainable exploration toolkit for small-scale, high-quality ore deposits (<5 million m^3), with the ultimate goal of reducing the EU's reliance on critical and strategic raw material imports (Müller et al. 2022). The project has selected three demonstration sites in Europe, including Tysfjord in northern Norway, which is known for its production of high purity quartz from NYF-type pegmatites.

The Geological Survey of Norway (NGU), one of the thirteen partners involved in the GREENPEG project, was assigned the task of evaluating the effectiveness of ground geophysics at several localities in Tysfjord. To date, only a few attempts have been made to apply Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) in pegmatite exploration (Raji & Bale 2022, Oyonga et al. 2015, Patterson & Cook 2002, 2004). However, through the utilisation of the aforementioned methods and careful consideration of the local geological conditions and petrological-mineralogical structure of the targeted pegmatite and its host rocks, it is demonstrated that GPR and ERT can yield valuable results for near-surface exploration of pegmatites within crystalline rock masses.

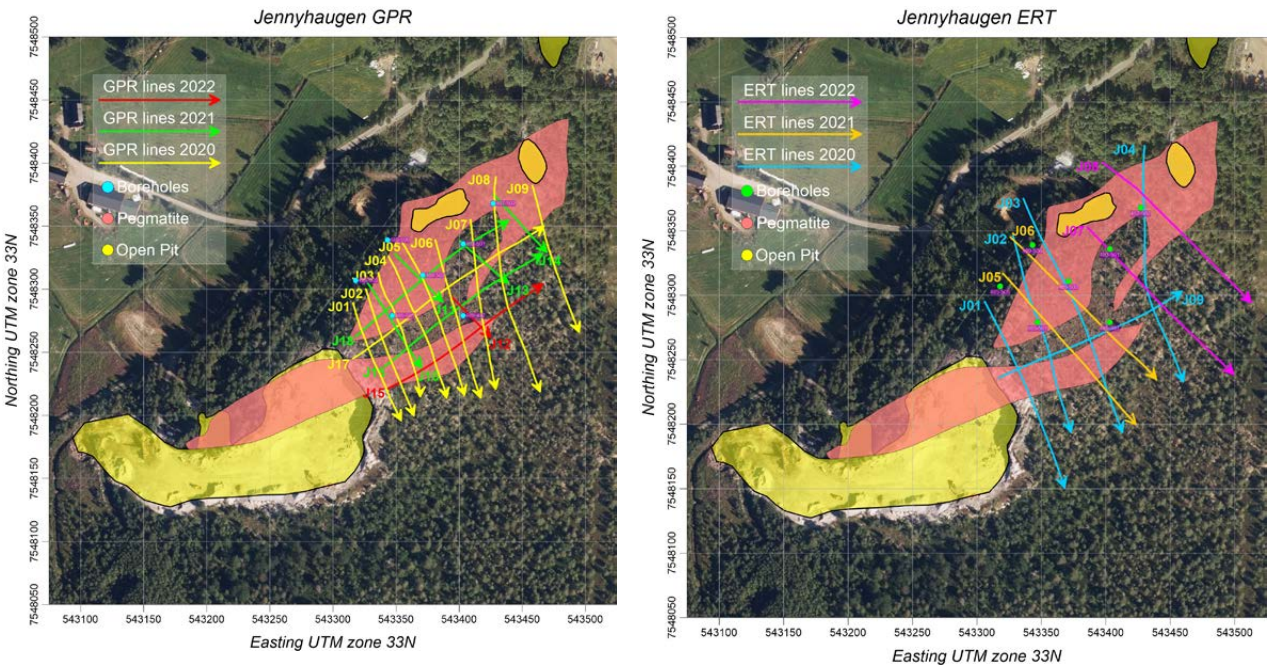


Fig. 1. GPR and ERT profile placement (colored lines) at Jennyhaugen relative to the scale and strike of the lens-shaped pegmatite body. Open pits marked in yellow, while red polygons indicate extended pegmatite bodies based on surface mapping.

METHODOLOGY

Throughout four field campaigns carried out in Tysfjord between 2020 and 2023, a total of more than 45 profiles were collected from various test sites. Among these sites, the Jennyhaugen open pit and Håkonhals quarry stood out as the most valuable locations for obtaining results due to the availability of borehole data. Ground-penetrating radar (GPR) data was acquired using the PulseEKKO PRO system, equipped with the Ultra Receiver unit by Sensors & Software. To achieve maximum depth coverage, 50 MHz antennas were utilised. Due to challenging terrain conditions and employing a high stack number (~15,000 stacks per trace sampling – approximately 3 seconds per measurement), the GPR measurements were carried out manually with antennas mounted on a frame. Electrical Resistivity Tomography (ERT) measurements, on the other hand, were performed using a Terrameter LS instrument by ABEM. The survey setup utilised either a two (Jennyhaugen) or five-metre (Håkonhals) electrode spacing accordingly to the pegmatite lens size and the Multiple Gradient array configuration (Lund system – Dahlin 1993).

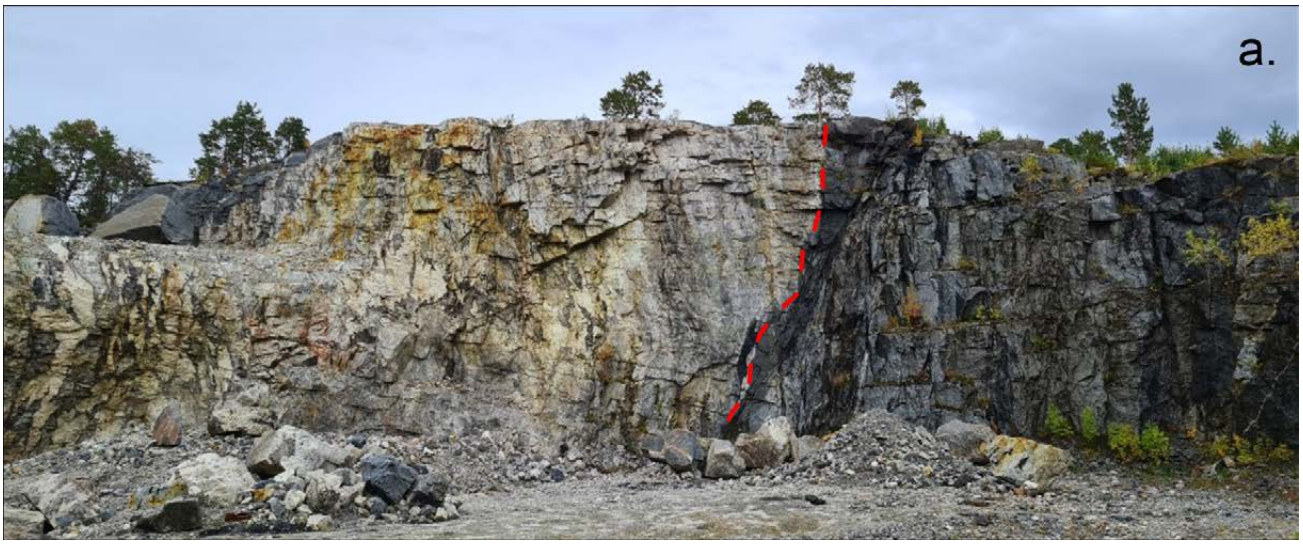
The Jennyhaugen open pit test site was extensively surveyed with a total of 18 GPR and 9 ERT profiles (2-metre electrode spacing), densely covering the pegmatite body in a non-normalised grid pattern (Fig. 1). Most profiles were designed to run either perpendicular or parallel to the strike of the pegmatite body. However, a few profiles were adjusted to fit a pre-existing borehole grid with a different NW-SE strike, aiming to enhance the interpretation success. In Håkonhals, 3 GPR and 2 ERT profiles were conducted over the gneiss and amphibolite covered pegmatite. Owing to the 5-metre electrode spacing utilised in ERT, a larger penetration depth was ensured to match the larger dimensions of the pegmatitic body. Concerning GPR, the achieved penetration of roughly 75 metres is marginally enough to reach the base of the pegmatite.

RESULTS

By utilising the lowest NGU in-house antenna frequency and employing thousands of stacks per trace collection, the Ground-Penetrating Radar (GPR) setting at Jennyhaugen achieved 40 to 45 metres penetration which are relevant to this survey, as determined and mapped by Electrical Resistivity Tomography (ERT). Figure 2a displays a photograph of the mine wall at Jennyhaugen, the location where geophysical profiling took place. The mine wall exhibits prominent sub-horizontal open exfoliation joints, and the red dotted line marks the inclined contact between the light-colored pegmatite and the darker Tysfjord granite gneiss. In Figure 2b, the processed radargram presents distinct sub-horizontal open fractures within both the pegmatite and its wall rock, which are interpreted as exfoliation joints and precisely mapped by GPR as multiple reflectors. Apart from offering valuable structural information, the radargram data allow differentiation between unweathered and weathered rock domains, as well as between medium-grained granite gneiss (strong GPR signal) and the massive core zone of the megacrystic pegmatite consisting of metre-sized quartz and K-feldspar crystals (weak or no GPR signal). Figure 2c, on the other hand, illustrates a more precise modelling of the pegmatite lenses through ERT. Based on surface mapping of pegmatite outcrops, resistivities above 30,000 Ωm can be correlated with pegmatite bodies, particularly their core zones.

Regarding the GPR data collected at the Håkonhals site, as depicted in Figure 3 (upper), a diverse range of reflectors was identified. Drawing from borehole information, the most distinct linear features can be linked to the interfaces between overlying gneiss and amphibolite, as well as between amphibolite and/or gneiss with pegmatite. Given the extensively deformed state of the pegmatite at this site, the pegmatitic body is rife with areas of strong dielectric contrast, giving rise to a complex array of reflectors that are challenging to interpret. Conversely, interpretation using ERT (lower part of Fig. 3) is considerably simpler. This is because the mylonised pegmatite gives rise to lower resistivities compared to the surrounding unaltered bedrock. This contrast in resistivity differs from our observations in Jennyhaugen, where the pegmatite appeared to be more resistive than the host rock. Essentially, this implies that site-specific conditions in pegmatite exploration should guide the interpretation framework.

a)



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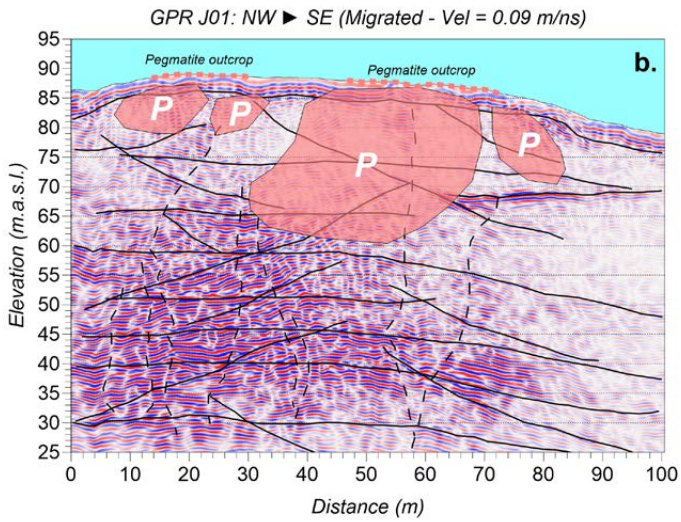

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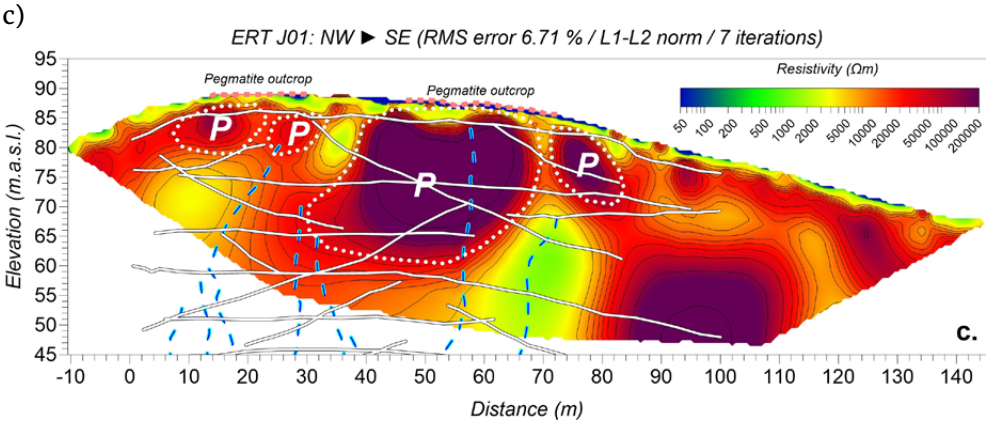

Fig. 2 a) Northeastern exposure of the Jennyhaugen open pit. On the left, the light rock represents pegmatite, while the dark grey rock on the right is Tysfjord granite gneiss. The wall reaches a height of approximately 20 metres. GPR and ERT profiles depicted in b) and c) are positioned around 25 metres behind the wall and run parallel to it. b) Processed GPR radargram for profile J01, featuring interpreted linear features (black lines) and pegmatite lenses outlined by ERT (pinkish rectangles). c) ERT inversion findings for profile J01, showcasing interpreted pegmatite lenses (white dotted lines) and visualising lineaments extracted from GPR (white and blue dotted lines).

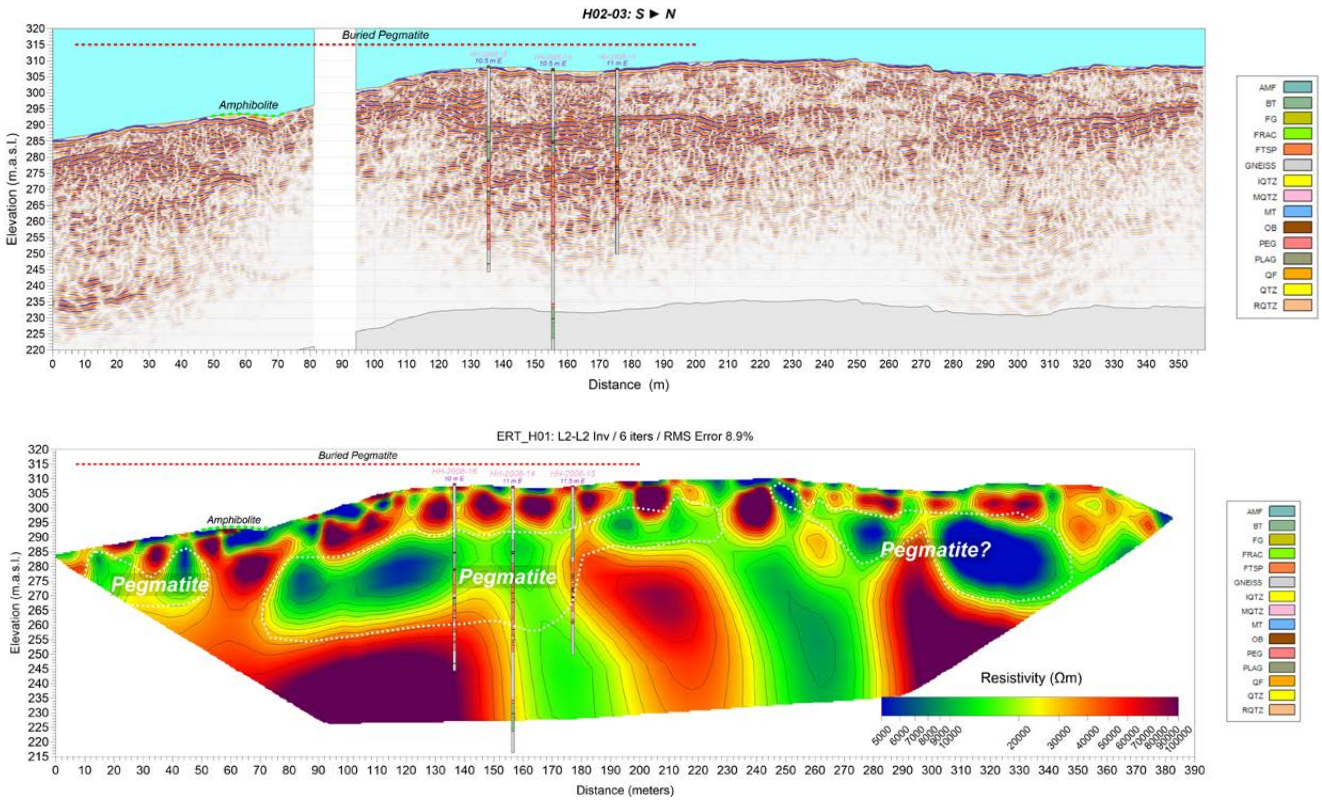

Fig. 3. Processed GPR (upper) and ERT (bottom) profiles from Håkonhals with borehole information along with pegmatite interpretations based on resistivity distribution (white dotted lines).

CONCLUSIONS

ERT profiling has revealed a distinct contrast between pegmatite and host rock, manifesting as highly resistive clusters when the host rock is deformed (e.g., Jennyhaugen site), or as conductive layering when the pegmatite itself is mylonised (e.g., Håkonhals site). Conversely, GPR profiling has provided in its traditional sense valuable insights into the geometric features of the pegmatite deposit, exhibiting a diverse range of reflectors that also help delineate the base of the pegmatite at depths where ERT resolution is limited. These findings affirm that ground geophysics, may serve as an effective and sustainable approach for delineating and characterising buried pegmatites. However, detection using ground geophysics is challenging due to the reliance on generic dielectric and geoelectric properties that are not specific or distinctive to pegmatites, such as low/high resistivity and/or low reflectivity.

REFERENCES

Dahlin, T. 1993. On the Automation of 2D Resistivity Surveying for Engineering and Environmental Applications. Dr. Thesis, Department of Engineering Geology, Lund Institute of Technology, Lund University.

Müller, A., Reimer, W., Wall, F., Williamson, B., Menuge, J., Brönner, M., Haase, C., Brauch, K., Pohl, C., Lima, A., Teodoro, A., Cardoso-Fernandes, J., Roda-Robles, E., Harrop, J., Smith, K., Wanke, D., Unterweissacher, T., Hopfner, M., Schröder, M. & Rausa, A. 2022. GREENPEG – exploration for pegmatite minerals to feed the energy transition: first steps towards the Green Stone Age. London: Geological Society, Special Publications 526.

Oyonga, O. A., Kudamnya, E. & Ugar, S.I. 2015. 3D Geoelectrical resistivity mapping of tourmaline-rich pegmatite in Angwan Doka, Nassarawa State, Northcentral Nigeria. International Journal of Science and Research 6, 1646–1650.

Patterson, J. E. & Cook, F. A. 2002. Successful application of ground-penetrating radar in the exploration of gem tourmaline pegmatites of southern California. Geophysical Prospecting 50, 107–117.

Patterson, J. E. & Cook, F. A. 2004. Ground Penetrating Radar (GPR) as an exploration tool in near surface pegmatite mining. 74th Annual SEG Meeting, Denver, Colorado. Abstract Proceedings: SEG-2004-1472.

Raji, W. O. & Bale, R. B. 2022. 2D electrical resistivity imaging of tantalite-bearing veins in Kaiama, Nigeria. NRIAG Journal of Astronomy and Geophysics 11, 306–312.

EARTH OBSERVATION TECHNOLOGIES IN THE TRANSFORMATION OF THE EXTRACTIVE INDUSTRY AND CHALLENGES

by

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Society and new European Union (EU) regulations demand a transition of the extractive sector, whereas at the same time resources are urgently needed. Due to the technological advances both in sensors and in image processing and analysis tools, Earth Observation (EO) data has a rapidly increasing potential in various fields, and the extractive sector is one of them. Lower ore grades, environmental restrictions, health and safety obligations, technological efficiency and social acceptance are some factors that will eventually impose the adoption of innovations in mining during the whole supply chain and mine life cycle (Steen et al. 2019). Nowadays, EO data and remote sensing techniques provide the capability to effectively monitor mining activities and their compliance with respective guidelines during their life cycle while being non-invasive and cost-effective, throughout all mine phases. Yet there isn't any integrative approach where the scientific knowledge of EO methods and applications systematically serves as tools for transforming the extractive industry. Therefore, besides the technical developments and implementation of innovative methods for analysing EO data, research in the 'Secure and Sustainable Supply of Raw Materials for EU Industry' (S34I – https://s34i.eu/) project aims to unlock the potential of EO data to support the sustainability transition of the extractive industry. An expected outcome also lies in decreasing supply chain risks and increasing transparency for stakeholders, thereby contributing to the achievement of the social license to operate (SLO). To do that, social survey methods like interviews and questionnaires are imple-

mented to capture the viewpoint of multidisciplinary stakeholders, highlighting the most crucial concerns and identifying potential opportunities to address them through EO. Moreover, collecting the existing datasets and the technical requirements corresponding to each use case defines the specifics of implementing EO data at each site and supports the technical part of the project with the relevant information to meet their objectives. The considering workflow is divided into four tasks.

The first task aims to identify a framework for the current and potential use of EO data in the extractive sector, operating both as a technological tool and sustainability reinforcer. Sustainable development, circular economy principles related to waste and materials, and social engagement actions concern not only the mining industry but also the public and the authorities. Joint legislation and company strategies are working towards the transformation of the sector.

The analysis of the mining value chain involved a multi-level approach to EO data use and its advantages. Initially, sustainability and circularity topics were listed, followed by key points for gaining social acceptance in the extractive industry. Indicators were filtered from official reporting systems and relevant literature, focusing on EO data applications in mining. Each indicator and subcategory were explored using literature sources, along with a description of the methods employed. The technical characteristics and outcomes of each case study are mentioned in the corresponding indicator. For instance, following the sustainability categorisation, under the Social scope, classes like H&S (Health & Safety), Transparency/communication and community positive impact are mentioned, getting more detailed subsequently. Additional information, like online news and company reports was used to map the current industrial perception of EO data and remote sensing techniques In the spotted topics, EO data directly contributes to the extractive industry by being a cost and time-effective tool that provides accurate results for monitoring the operation, resulting in the industry's transition.

The second task under the project aims to identify how EO-based methods can promote transparency in communication and social responsibility. In addition, the project will determine how the EO method can provide effective monitoring and independent assessment of mining activities to ensure responsible mining. A bibliographic review evaluated how EO methods have been used by mining companies, authorities, and Non-governmental organisations (NGOs) to monitor mining activity, their reliability and problematics, and their relevance to support SLO at different stages of mining operations.

The research shows that companies use EO methods mainly when operating in sensitive environments or for monitoring environmental impacts, but also for monitoring low-accessible areas and dams. Authorities and NGO's use EO data to monitor industrial activity, especially to point out transcending activities and environmental impacts. Some limitations and uncertainties in EO data use and data interpretation emerged from the study. To gain a deeper understanding, a diverse group of stakeholders is directly engaged. Interviews, focus group discussions and questionnaires run in the local language at some of the project sites. Data collection is accomplished via direct contact with their representatives through customised invitations, highlighting the relevance of their organisation's input. In Finland, for a wider audience, a link to a questionnaire is published in the local newspaper and an informal colloquial approach also being tested (Fig. 1). Expected outcomes are raising awareness of the EO-based methods amongst companies and authorities, so they use them when applicable. There has been reluctance to participate in the survey or in engaging in the discussion from all stakeholders. From the first results, it seems that the community is aware of UAVs and satellites to some extent, but it is a difficult matter in which some do not feel having enough expertise and

ability to provide their own views of the matter. As the project addresses both land exploration and shallow waters systematic mineral exploration, this raises the need to consider an integrative methodology of shallow waters and land-use planning for economic usage of these areas, such as fishing and tourism, and other use needs to ensure responsible mining. It will consider local perception, land-sea connectivity, as well as environmental challenges related to the exploration campaign of respective CRMs. Thus, Task 3 focuses on the shallow waters site. Rias Baixas (Spain) has suitable geological conditions (Fig. 2) onshore or offshore for significant CRM mineralisation (EC 2020). Conventional methods of marine minerals exploration are costly and time-consuming and can have environmental impacts on ecosystems, hefty vehicles circulating on the seafloor (Miller et al. 2018). Sea mining development and its technological solutions are being discussed lately, despite the concern about the impacts on the ecosystem on the seabed (Kleiv & Thornhill 2022). Underwater hyperspectral imaging (UHI) is a promising and non-invasive tool for the automated identification of diverse features in the seafloor in scales varying from millimetres to hundreds of kilometres, providing close-range observations (Montes-Herrera et al. 2021).

Fig. 1. Survey in Finland.

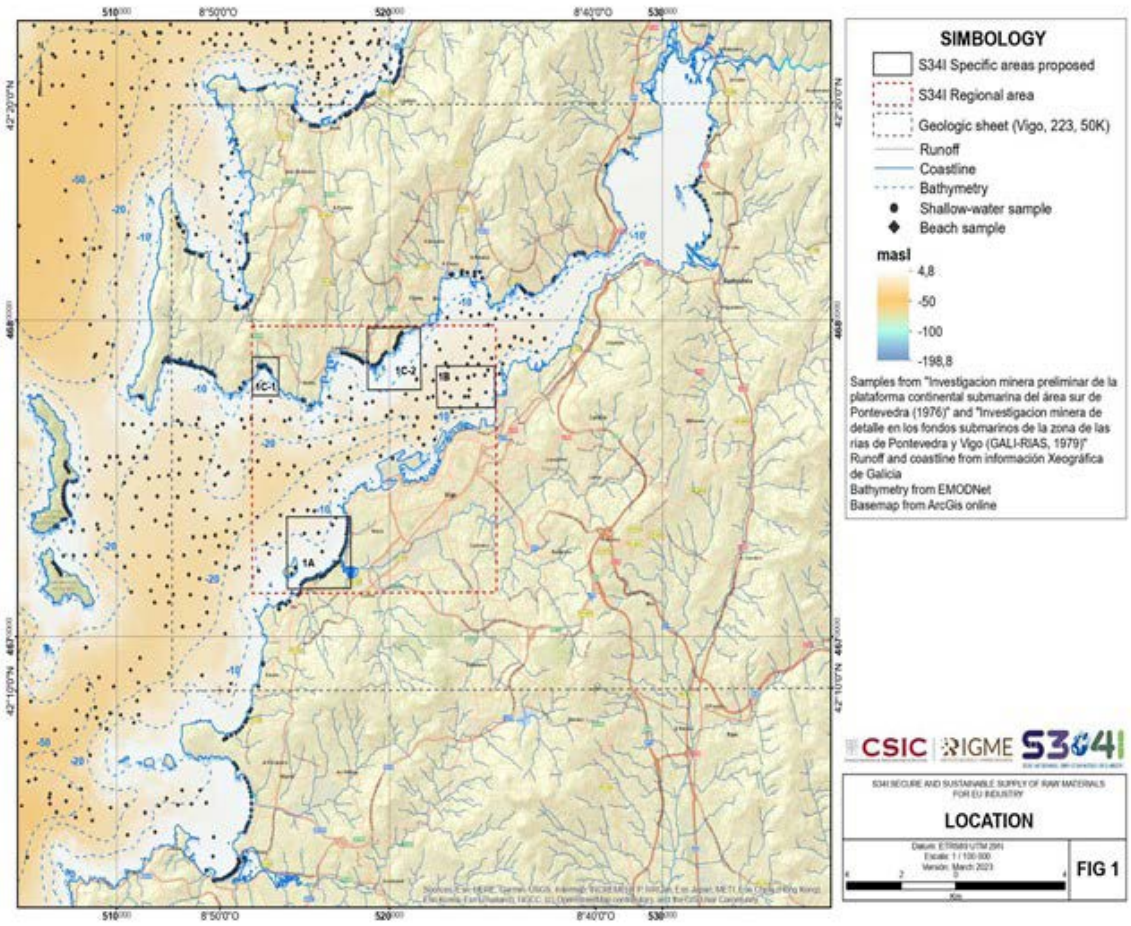

Fig. 2. Rias Baixas geological map.

The research methodology adopted is a combined method developed in two phases. The first consists of a survey applied to the stakeholders of the Ria de Vigo area, whereas the second phase will be a follow-up interview study. Answers will be analysed statistically to gather opinions, concerns, and suggestions that can provide guidelines for better communication between the stakeholders and exploration companies or researchers. The questionnaire was elaborated and validated, and inter-observer reliability was defined and is now being applied to stakeholders of the area. A follow-up study involving in-person interviews is planned to take place later. The content analysis will be conducted with inter-observer reliability. The results of the survey will provide insights into the knowledge and perception of the local community about the needs and use of mining and remote sensing methods applied to mining, as well as the doubts and concerns of the stakeholders. The results will demonstrate the potential of EO data, best practices and requirements.

The importance of the last task lies in the application's impact of EO technologies in mining, with several benefits, such as reduced operation risks and the impact on the environment, increased digitalisation and process efficiency of mining operations. The challenges that need to be faced are lack of clear value propositions, insufficient awareness of EO technology among mining stakeholders and understanding of the limitations of EO data. Forms developed for each pilot site will try to gather relevant information from the sites to best adapt the EO technologies to the technical requirements and key objectives that the sites want to achieve, and all the information collected will be used in the rest of the project tasks to better understand the requirements and needs of each site. The methods are based on:

- Site identification: different sites have been identified and the corresponding owner;
- Characteristics of each site: general information was collected on each site to define the exact location and geological and mining characteristics;
- Forms elaboration according to the mining phases: for each mining phase, a form has been elaborated according to the stage of the mining phase, and different questions regarding the technical requirement have been formulated;
- End-users' identification: end-users from each site have been located and identified;
- Deliver the forms to the end-users: once the forms have been completed, one form per site has been sent to the end-users identified;
- Collect and analyse the information obtained from the end-users: the final step is to analyse the information received from the sites. All the information and data received are compiled into a form that describes the main requirements expected of each site.

The outcomes expected to be obtained in this task will be the definition of the requirements from each site for building trustable EO-derived information to support the mining permitting processes. The information will be used to develop a more specific EO data analysis workflow for each site and its needs according to the mining phase. Gathered data will serve other parts of the S34I project to elaborate a more accurate system with all needs covered.

ACKNOWLEDGEMENTS

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REFERENCES

EC 2020. Critical Raw Materials Resilience: Charting a Path towards Greater Security and Sustainability. COM (2020) 474 final.

Kleiv, R. A. & Thornhill, M. 2022. Deep-Sea Mining–A Bibliometric Analysis of Research Focus, Publishing Structures, International and Inter-Institutional Cooperation. Minerals 12(11), 1383.

Miller, K. A., Thompson, K. F., Johnston, P. & Santillo, D. 2018. An overview of seabed mining including the current state of development, environmental impacts, and knowledge gaps. Frontiers in Marine Science 4, 418.

Montes-Herrera, J. C., Cimoli, E., Cummings, V., Hill, N., Lucieer, A. & Lucieer, V. 2021. Underwater hyperspectral imaging (UHI): A review of systems and applications for proximal seafloor ecosystem studies. Remote sensing 13(17), 3451.

Steen, J., Macaulay, S., Kunz, N. & Jackson, J. 2018. Understanding the Innovation Ecosystem in Mining and What the Digital Revolution Means for It. In: Clifford, M., Perrons, R., Ali, S. & Grice, T. (eds) Extracting Innovations: Mining, Energy, and Technological Change in the Digital Age. New York: CRC Press.

ARTIFICIAL INTELLIGENCE AND EARTH OBSERVATION FOR EFFICIENT RAW MATERIALS MAPPING

by

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The Secure and Sustainable Supply of Raw Materials for EU Industry – S34I project aims to increase European autonomy over raw materials resources through research and development of new data-driven methods for the analysis of Earth observation (EO) data. The aim is to improve the systematic exploration of minerals and ensure continuous monitoring of all activities, i.e., extraction, closure, and post-closure. The project involves 19 partners from 12 European countries. The partners have balanced expertise and come from large industries, SMEs, private non-profit and public research organisations, public institutions, and academia.

The project uses various techniques and methods, including satellite data, airborne systems, unmanned aerial vehicles (UAVs), underwater hyperspectral imaging (UHI), ground-based measurements, and traditional in-situ methods. We are using a cloud-based geospatial processing infrastructure based on Cloud-Ferro Copernicus DIAS, which will enable the development of advanced methods and models derived from EO data. Using artificial intelligence, we are supporting the technical experiments and pilot validations/demonstrations for the six pilot use cases in:

- *Onshore exploration* (Áramo, Spain), where the epithermal (epigenetic) mineralisation of Cobalt-Copper-Nickel is hosted within certain stratigraphic limestone units within the Upper Namurian of the Carboniferous Period.

- *Shallow water exploration* (Ria de Vigo, Spain), where the geological conditions onshore and offshore shallow waters are suitable for placers finding (primary mineral source, weathering environment, means of transportation).
- *Extraction* (Gummern, Austria), a quarry that produces roughly 1 million tons of high-quality marble, both in open-pit and underground extraction sites. 400000 tons of material must be transported to local waste dumps, as this material does not fulfil the quality criteria of the major customers in the pharma, paper, and automotive industries.
- *Closure/post-closure* (Lausitz, Germany, Aijala and Keretti-Outokumpu, Finland). The Aijala mine and processing plant in Southwest Finland closed in 1961. The tailings are 2 million tons, of which a small part is placed as mine backfill with the side stone. The Lausitz mining and post-mining landscapes cover approx. 7000 km^2, including many refilled small- to large-scale former pits, remaining lakes, open active and inactive pits and channels used to release pumped water to surface water bodies.

Fig. 1. S34I pilot site locations and their characteristics, including deposit types and land cover/land use.

Mining sites were selected from key EU mining regions, with criteria covering all phases of life-cycle mining and different sizes and Critical Raw Materials. S34I aims to take a holistic view to cover all challenges identified in the theme and has searched for accessible and representative sites for the use cases.

The cloud infrastructure put in place enables the analysis of geospatial data from a whole range of EO sensors (radar, multispectral, hyperspectral, and thermal), the integration and processing of data from different sources (satellite, UAV, UHI, in-situ) and the analysis of datasets for the challenges prioritised at each mining pilot site. We are developing prototype implementations for promising algorithms for data integration and processing, spatial analysis, spatial monitoring, modelling, and mapping. The focus is on technologies such as artificial intelligence (AI) and machine learning (ML), geospatial artificial intelligence (GeoAI), Big Data

processing, knowledge representation, modelling and mathematical optimisation. In particular, the innovative, promising methods for the prototype are used:

- *At the onshore exploration site*, where improved maps and techniques to map potential Co target areas using support vector machine (SVM), random forest (RF) and artificial neural networks (ANN) to create an ensemble AI method and exploit different satellite-based datasets (Landsat-9, Sentinel-1, Sentinel-2, PRISMA and WorldView-3) are developed. Co-predictive mapping improves by using self-organizing map (SOM) for pre-processing exploration datasets and combining geological and remote sensing based models to detect the hydrothermal alterations associated with Co.
- *At shallow waters exploration site*, where AI/ML post-processing of UHI to build a spectral library for ground-truthing and correlation with onshore Earth observation data (PRISMA, Worldview, Sentinel, Landsat-8/9) that allows proposing a new methodology for ground truthing and detection of mineral deposits in coastal areas. Shallow waters and shoreline sediment distribution are geologically studied regarding the placers' deposit occurrences to delineate the prospective areas.
- *At the extraction site*, improved volume maps of mining waste deposits using Structure from Motion (SfM) photogrammetry using a multispectral camera mounted on a UAV with an operational range compatible with Sentinel-2 are being used. Ground instability maps are obtained through new InSAR methods for the combination of multiple-satellite SAR data (e.g., Sentinel-1 and COSMO-SkyMED) collected at different bands to compute long-term 2D (up-down, east-west) ground displacement time-series on a high-resolution (HR) grid. Mineral stockpile volume estimation through satellite photogrammetry and 3D-stereo images from optical and SAR data is being computed.
- *At closure/post-closure site*, where ground instability maps by SBAS-InSAR are analysed on Sentinel-1 enhanced super-resolution datasets obtained through DL models trained on VHR space-based datasets from Copernicus Contributing Missions (i.e., TerraSAR-X, CosmoSkyMed, ICEYE). Acid mine drainage (AMD) maps by AI predictivity of Fe (and other AMD constituents) and quantitative pH mapping using RF, ANN, and SOM and exploiting Sentinel-2 and other HR Earth observation datasets are estimated.

In S34I, we are developing a multi-scale and multi-platform analysis methodology to coherently exploit EO data from different spatial and spectral scales obtained from different remote sensing platforms, mainly satellites, airborne and UAVs. This methodology will be a basis for building processing pipelines for local, regional, national, and European geoscience services.

Space-based remote sensing and geospatial information harmonisation developed by the project team ensures that state-of-the-art modelling and geological mapping comply with EU data quality principles and EDGI mechanisms for harmonisation and standardisation of interoperability. We pay particular attention to improving geological integration at the land-sea interface and ensuring that research datasets become open, unbiased geoscience data for future use by researchers, policymakers and society at large.

In addition to space-based data collection, special attention is also given to non-space-based methods. We focus on in-situ data collection both on land and in shallow waters, either to create the required spectral libraries that can be used as ground truth/calibration of EO methods or to generate quality datasets for training AI models and make them available as open, high-quality datasets. A ground truth spectral library on the seabed in shallow waters using UHI survey

data and a ground truth spectral library on land exploration sites using visible and near-infrared (VNIR) – shortwave infrared (SWIR) survey data are currently being created. We are acquiring airborne very high-resolution (VHR) Light Detection and Ranging (lidar) and hyperspectral datasets and applying data fusion techniques. These data are processed using the algorithms of ML to automate the pre-processing of aerial hyperspectral data. In doing so, only a minimal amount of ground truth data is required to avoid lengthy and expensive field survey campaigns, and only a minimum of expertise and tuning is required for mineral identification. Hyperspectral data processing, mineralogical characterisation, site mining waste deposits extraction, and in-situ geochemical sampling in water and solid soil complement EO data collection.

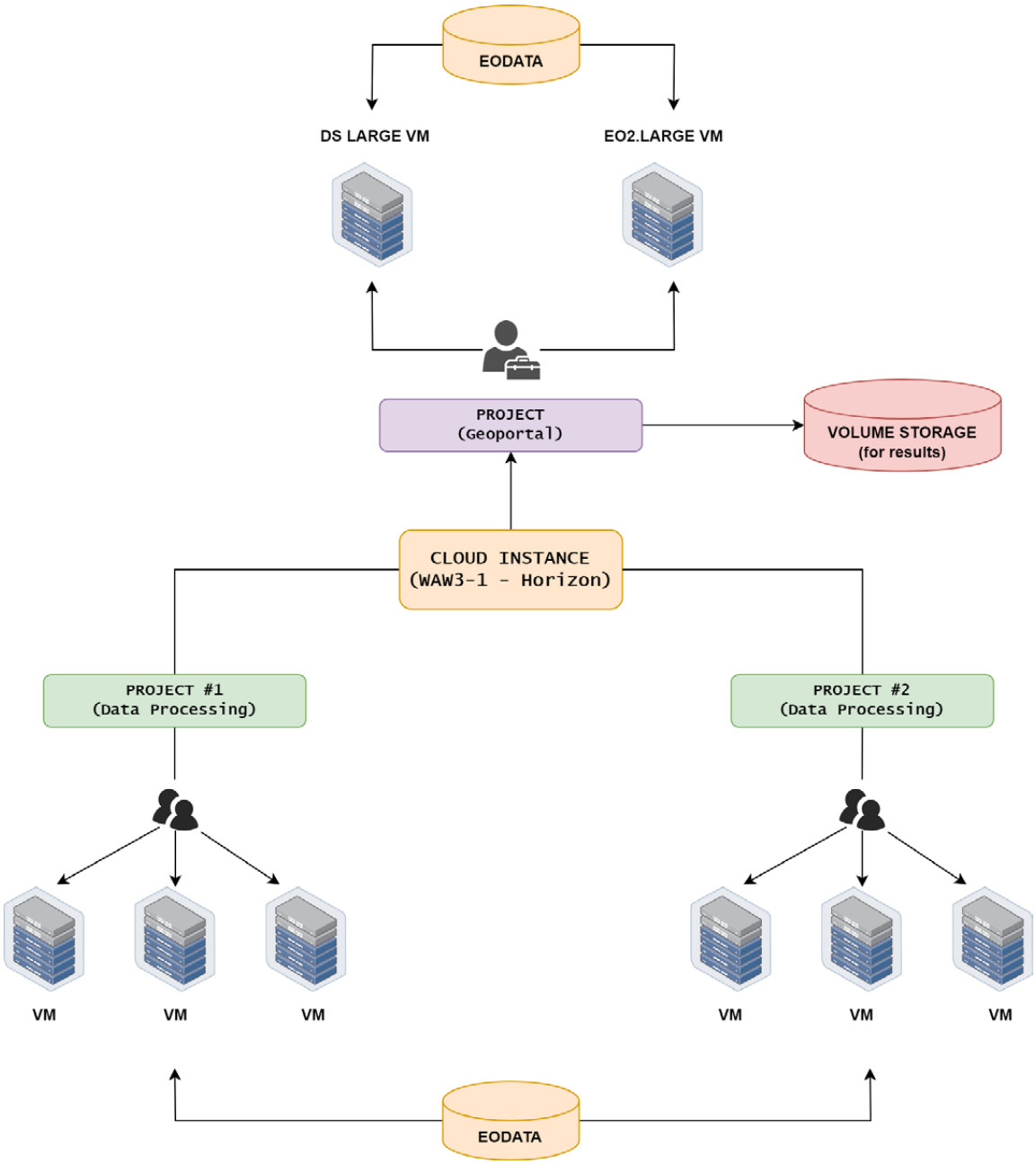

Fig. 2. CloudFerro Copernicus DIAS geospatial processing infrastructure.

Prototype processing pipelines for promising algorithms for data integration and processing, spatial analysis, spatial monitoring, modelling, and mapping are being developed. The pipelines of methods and prototyping EO-based added value services for mining stakeholders are being prepared for three services categories:

- *Raw materials deposits mapping*, using the EO-based services related to gaining geospatial intelligence on new or more accurate existing Critical Raw Material deposits. This applies to both land and shallow water exploration sites.
- *Early warnings*, to develop the EO-based services related to early warnings to reduce workers and surrounding population risks (including instability and volumes). This applies to both extraction and closure sites.
- *Environmental monitoring*, to apply EO-based services related to environmental monitoring on health and ecosystems. This applies to both extraction and closure sites.

We are running benchmarking and synergies among various methods for similar purposes to support decisions in different phases of the mining life cycle at different scales.

The value of the results will be demonstrated to stakeholders, i.e., geological surveys, the mining industry, local communities, and policymakers. The project will support future systematic mineral exploration and continuous monitoring of extraction, closure, and post-closure activities to promote the secure and sustainable supply of raw materials to Europe while enhancing its resilience and independence from non-EU sources.

HYPERSPECTRAL EXPLORATION VECTORS IN THE CENTRAL EUROPEAN KUPFERSCHIEFER DISTRICT

by

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In order to realise the objectives set forth by the Green Deal's climate targets, facilitate the concurrent shifts in energy and digital landscapes, and promote sustainable economic growth, the European Union (EU) must ensure a consistent and reliable supply of raw materials. Presently, over 80% of the EU's raw material demand is met through imports, a reliance that significantly heightens the susceptibility of European industrial and strategic supply chains to potential disruptions. Europe has a long and rich mining tradition and has significant potential for uncovering future reserves of essential metals, including lithium, cobalt, zinc, copper and many other elements crucial for renewable energy and digital advancements. However, environmental and social challenges limit the acceptance of the mineral and mining sector in Europe, and much of the European subsurface needs to be better understood. Through funding from the EU Horizon initiative, the VECTOR project introduces an innovative, human-centric approach that considers both environmental-social sustainability and technical viability as foundational prerequisites for mineral exploration and extraction. This approach centres on the fusion of geological indicators for ore discovery with social factors that signal the potential for mutually beneficial mineral development. By amalgamating these aspects, the project aims to pinpoint economically and ecologically viable ore deposits, thus establishing a framework that harmonises the imperatives of environmental responsibility and economic advancement.

The project's geoscientific methodology aims to create a novel set of mineralisation indicators through the utilisation of machine learning algorithms, which will identify correlations drawn from a diverse range of geoscientific criteria. This process involves the aggregation of extensive historical data alongside the implementation of environmentally conscious exploration tools like ambient noise seismic and hyperspectral imaging. Through these measures, we intend to construct an exhaustive repository of critical geoscientific parameters, encompassing petrophysical, geophysical, geochemical, and mineralogical data. We will use that database to develop accurate models of subsurface geology and vectors towards ore in three European sediment-hosted mineral systems that have an exceptional endowment in critical raw materials and significant exploration potential: (i) the Irish Midlands basin, characterised by carbonate formations hosting hydrothermal

stratabound Zn-Pb mineralisation, which stands as Europe's principal source of zinc, (ii) the Central European Kupferschiefer district containing a series of stratabound hydrothermal ore deposits that comprise Europe's largest Cu and Ag-resource, and (iii) the unique Jadar Li-B deposit in Serbia, discovered by Rio Tinto in 2004, and arguably one of the World's largest rock-hosted Li resources.

Within this contribution, we present the initial findings from a hyperspectral imaging campaign on drill cores extracted from the European Kupferschiefer district, a component of the VECTOR project's overarching research. The utilisation of hyperspectral imaging offers an efficient, high-resolution, non-invasive means of mapping minerals across the complete length of drill cores with continuous spatial coverage. Operating within the infrared range, this spectroscopic method captures the spectral reflectance and emission across hundreds of spectral bands, leveraging electronic and vibrational processes within minerals to provide insight into geological compositions. Hyperspectral drill core imaging is increasingly employed in the exploration industry. By enhancing conventional geological logging practices and complementing lab-based petrographic and geochemical examinations, this technique facilitates the comprehensive characterisation of ore deposits. Through a preliminary investigation centred on Kupferschiefer-type mineralisation (Géring et al. 2023), we successfully showcased the capacity of hyperspectral imaging to identify and quantify critical redox boundaries, such as the notable *Rote Fäule* alteration, as well as potentially significant alteration minerals like hydrothermal kaolinite and ferroan carbonates. The abundance of data resources within the VECTOR project offers an unprecedented opportunity to gauge the practicality of these alteration indicators for exploration vectoring and the comprehensive delineation of mineral systems on a larger scale, particularly concerning sediment-hosted copper systems. This initiative stands poised to contribute substantially to our comprehension of alteration proxies, their utility in guiding exploration efforts, and the broader characterisation of extensive mineral systems.

In July of 2023, a comprehensive hyperspectral scanning campaign was undertaken, encompassing roughly 1500 metres of drill core across 70 boreholes strategically distributed throughout the expansive Spremberg–Graustein Kupferschiefer exploration zone located in Lusatia, Germany. The curated selection of core samples features five extensive and uninterrupted intervals sourced from three boreholes, alongside their associated wedges, initially drilled by Kupferschiefer Lausitz (KSL) between 2009 and 2010. Additionally, the compilation consists of 65 more succinct intervals originating from boreholes drilled during the period spanning 1957 to 1979, a component of the Spremberg exploration initiative executed by the former German Democratic Republic (GDR). Stratigraphically, the KSL cores extend from the Rotliegend (Permian) sandstones and conglomerates in the footwall, through the Kupferschiefer *sensu stricto*, progressing upwards to encompass the superimposed strata of Zechstein marls, carbonates and evaporites, and, for one of the holes, also the base of the Buntsandstein. The GDR drill cores, housed at the drill core repository of the Geological Survey of Brandenburg (LBGR), predominantly cover a few metres around the immediate intersection of the Kupferschiefer black shales.

For hyperspectral data acquisition, we used a container-housed Specim SisuROCK drill core scanner setup with a full suite of sensors covering the visible-near infrared (VNIR), short-wave (SWIR), mid-wave (MWIR) and long-wave infrared (LWIR) spectral regions. We pre-processed the raw data in near-real time using a custom-built processing pipeline that automatically identifies new datasets, applies sensor corrections and then co-registers the hyperspectral data from each sensor. After co-registration, background pixels were semi-automatically masked from

each tray, and the data were mosaicked (per sensor and drill hole) for subsequent analyses. We then generated basic visualisations such as band ratios and minimum wavelength maps using the open-source Python package *hylite* (Thiele et al. 2021). These maps are utilised for on-site quality control and guide the selection of samples used to train supervised, machine-learning-based methods that aim to upscale mineral abundance estimates across all boreholes using quantitative mineralogical data (e.g., Tusa et al. 2020, De la Rosa et al. 2021).

Our current efforts involve the aggregation and organisation of hyperspectral data, for example by the systematic arrangement of drill cores based on their location or mineralisation grade (Fig. 1), in order to find trends and correlations. By doing so, we aim to evaluate the variation of spectral indices and their usefulness for exploration vectoring laterally within the expanse of the Southern Permian Basin. Eventually, the hyperspectral data will be combined with geological, geophysical, and geochemical constraints to derive comprehensive and accurate 3D subsurface and 4D mineral system models of the Kupferschiefer Basin. The knowledge gained from this interdisciplinary approach will advance our understanding of the complex interplay between geological processes, mineralisation factors, and spatial distribution, paving the way for more effective exploration and resource management strategies in similar geological settings worldwide.

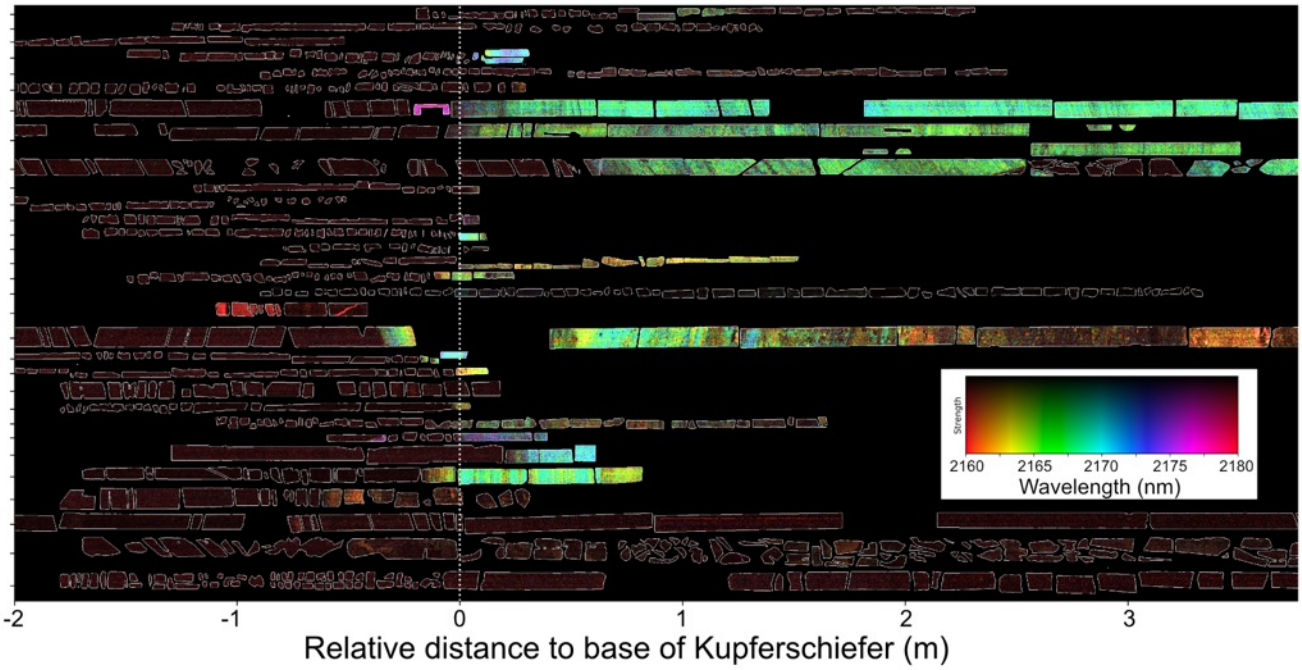

Fig. 1. Compilation of 32 hyperspectral drill cores from the Kupferschiefer in the Spremberg-Graustein area. Visualisation using minimum wavelength mapping on hull corrected spectra from 2125 to 2190 nm, targeting the doublet feature associated with kaolinite. The cores are arranged according to decreasing maximum Cu grade from top to bottom. The white line indicates the base of the Kupferschiefer; the stratigraphic top is towards the left.

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REFERENCES

De La Rosa, R., Khodadadzadeh, M., Tusa, L., Kirsch, M., Gisbert, G., Tornos, F., Tolosana-Delgado, R. & Gloaguen, R. 2021. Mineral quantification at deposit scale using drill-core hyperspectral data: A case study in the Iberian Pyrite Belt. Ore Geology Reviews 139, 104514. Available at: https://doi.org/10.1016/j.oregeorev.2021.104514

Géring, L., Kirsch, M., Thiele, S., De Lima Ribeiro, A., Gloaguen, R. & Gutzmer, J. 2023. Spectral characterisation of hydrothermal alteration associated with sediment-hosted Cu–Ag mineralisation in the central European Kupferschiefer. Solid Earth 14(4), 463–484. Available at: https://doi.org/10.5194/se-14-463-2023

Thiele, S. T., Lorenz, S., Kirsch, M., Acosta, I. C. C., Tusa, L., Herrmann, E., Mockel, R. & Gloaguen, R. 2021. Multi-scale, multi-sensor data integration for automated 3-D geological mapping. Ore Geology Reviews 136, 104252. Available at: https://doi.org/10.1016/j.oregeorev.2021.104252

Tusa, L., Khodadadzadeh, M., Contreras, C., Rafiezadeh Shahi, K., Fuchs, M., Gloaguen, R. & Gutzmer, J. 2020. Drill-Core Mineral Abundance Estimation Using Hyperspectral and High-Resolution Mineralogical Data. Remote Sensing 12(7), 1218–1223. Available at: https://doi.org/10.3390/rs12071218

GOLDENEYE PROJECT RESULTS AND IMPACT ON MINING

by

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Improved use of Earth observation with sensor and positioning data can offer significant exploitation and environmental control benefits and increase the productivity of mines. The EU-funded Goldeneye project has developed a GoldenAI platform, which can fuse high-resolution data from satellites, drones, and in-situ sensors to generate new high-resolution data from an entire mine. This data is being processed and converted into actionable intelligence with new tools developed in the project, offering improvements to exploration, mine safety, environmental monitoring, exploitation, and increasing extraction in pilot mines. The project has combined remote sensing and positioning technologies and taken advantage of Earth observation and Earth GNSS data with data fusion and processing powered by data analytics and machine learning algorithms. The GoldenAI platform and other developed technologies have been piloted in five trial mine sites across Europe and the results are presented in this paper.

INTRODUCTION

The modern society is dependent on minerals and raw materials. Although there is pressure to increase the use of recycled raw materials for sustainability, the excavation remains important as the need for raw materials is ever increasing (Johnson 2018). It is not possible to re-use all the waste due to ineffective and difficult separation processes and controversial environmental effects (Li et al. 2018). Thus, the amount of circulated raw materials remains limited due to challenges in recycling. The Goldeneye project use cases, described later in this paper, contributed to a positive impact on the EU economy and society in relation to access to raw materials. In the scope of Goldeneye project, the data sources can be divided into three categories: satellite-based sensors, drone (UAV)-based sensors,

and proximal sensors (Fig. 1). Measurement technologies used in case of drones were visual, infrared, multispectral, hyperspectral, and electromagnetic imaging. The proximal (ground-based) sensors included Active Hyperspectral Sensor (AHS) and Time-gated Raman spectrometer. In addition, GNSS underground geolocation was tested and developed.

GOLDENAI PLATFORM

One of the main results of the Goldeneye project is the GoldenAI platform. It was operational in 2022 and has been piloted in the field trials described in this paper. The use-cases of the Goldeneye platform address the different phases of the mine's life cycle from exploration to closure and post-closure.

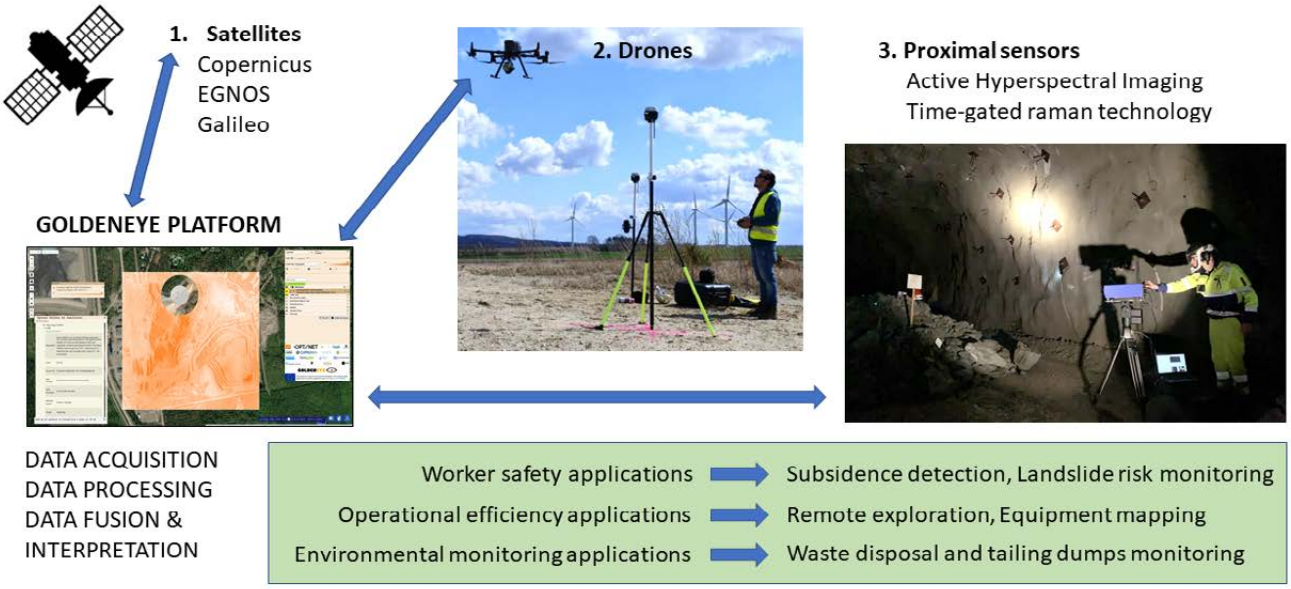

Fig. 1. GoldenAI platform fuses data from satellites, drone missions and in-situ measurements.

The applications developed in the project include mineral detection, safety monitoring, operational management, geohazard monitoring, and environmental monitoring. Monitoring produces large amounts of data in the form of images and spectrographs. Therefore, there are challenges in fast and timely analysis of acquired data (Filchev et al. 2018). Working with a wide set of different types of data is time consuming and requires a lot of expertise. The GoldenAI platform that enables novel uses of EOD in the mining industry is an answer to this problem. The GoldenAI platform enables the fusing of satellite, drone and in-situ data with automated data pre-processing and state-of-the-art visualisation methods. The visualised analytical maps are accessible to the mining site operators with simplified end-user experience without the need for in-depth knowledge of how the data is collected and pre-processed (Fig. 2).

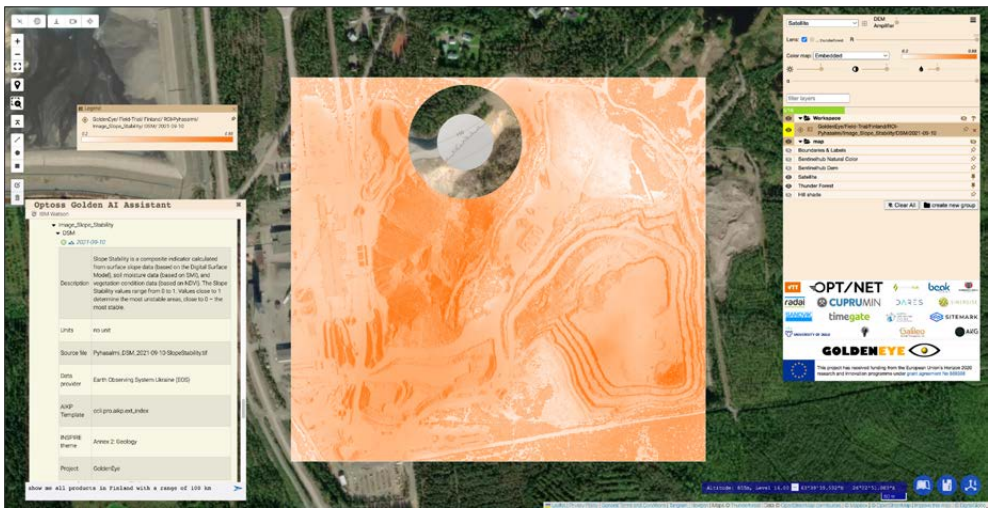

Fig. 2. The GoldenAI GUI visualisation of AI results: Slope Instability Index maps for 2021-09-10 for the area of Pyhäsalmi (Finland).

THE FIELD TRIALS AND RESULTS

There were five trial mine sites in the project, where the project technologies were developed and tested. The sites represent multiple phases of mining cycle from exploration to post-closure:

- FINLAND (underground extraction): Integration of UAV data with satellite data to monitor slope integrity, both open pits and tailing ponds. The GNSS geolocation to ensure re-user safety.
- GERMANY (exploration): Mineralogical knowledge – Integration of high-resolution UAV EM data with ground-based Raman and AHS data to help to identify drilling targets for Li and Sn.
- BULGARIA (exploration): Mineralogical knowledge – Integration of Infrared (IR) and Multispectral UAV data together with GIS-based maps of alteration mineral assemblages for Cu-porphyry and Au-epithermal targets.
- KOSOVO (8 tailing ponds, post-closure): Safety & environmental monitoring – Monitoring the stability of the Pb-Zn mine tailings using InSAR technique and evaluating the degree of acid mine drainage. Secondary extraction potential for Bi, Ga, Ge, In, Se, Te.
- ROMANIA (open pit extraction): Mineralogical knowledge & environmental monitoring – Integration of satellite data and drone or proximity data to improve mineral predictions and slope stability for open pit Cu-porphyry mine.

The German field trial demonstrated the abilities of Goldeneye platform and EO, UAV and proximal data gathering for development of bedrock analysis for exploration and change detection for environmental monitoring. Secondly, there was a use case in Bockau, where EO data was tested for identification of tectonic surface structures based on soil moisture differences. Thirdly, the pilot included a use case, where ground deformation was monitored in Knappensee at a former open pit, which is now flooded. The exploration use cases included 2D and 3D modelling of the ground mineralogy in exploration areas, 2D mineralogical mapping of outcrop walls, hand specimen analysis and mineralogical mapping of ancient mining shafts. The mineral exploration targeting of the German site in Bockau / Erzgebirge with drone-based LiDAR and electro-magnetic (EM) mapping, in

combination with proximal sensing using active hyperspectral scanning (AHS) of outcrop walls together with mobile Raman and XRF measurements directly in the field at the outcrop, has significantly reduced the time needed to capture mineral data as well as its required processing. The new Goldeneye techniques allow for more environmental-friendly mapping of the minerals in the underground with a reduced environmental impact fingerprint.

In Bulgaria, five pilot areas around porphyry-copper (Vlaykov Vruh and Tsar Assen) and epithermal gold systems (Elshitsa, Radka and Krassen) deposits were studied in the southern part of Panagyurishte area. The Goldeneye tools aim to reduce the time for prospecting and exploration targeting and thus increase efficiency and decision making in mineral exploration. Ga, Ge, In, Bi, Se and Te enrichment in the Cu-pyrite ores from Panagyurishte area need special attention and assessment as possible by-products of the future with potential for exploration. As a result, the resources and time needed for the survey are significantly lower using Goldeneye tools, hence saving exploration targeting costs for target assessment and decision making and raising interest for potential investors. The provided field trials tests in Panagyurishte demonstrate intelligent exploration scenario solutions for Cu-porphyry and Au-epithermal deposits and contribute for development and optimisation of multisource Earth Observation Data platform to improve the complete lifecycle of a mining operation.

The pilot in Roșia Poieni, Romania, developed tools for improving safety and environmental monitoring as well as optimising the extraction of copper minerals in an open pit mine. The aim is to improve the profitability of a low-grade copper mine through improved control over the extraction process as well as to reduce the environmental footprint of the mine. As a result, drone-based 3D-mapping of the open pit at Roșia Poieni has enabled more precise planning of the mine ore extraction and beneficiation. Creating improved drilling and blasting 3D designs with exact positioning has increased the effectiveness of the blasting works. Using the data provided by Goldeneye, the operating company Cuprumin has reduced the required effort to compile quarterly reports to 5-6 working days, instead of spending 5-6 weeks of engineer's time. The Goldeneye technologies have provided tools for monitoring of the disposal fluid material (using proximal sensing with a sonar) in the tailing pond and the stability of the dam. Furthermore, the project is reducing the risks of falling debris from above by monitoring the stability of the old benches, and waste dumps. Monitoring the stability of the slopes using Goldeneye platform is seen as the future tool since it will save resources and costs compared to manual inspection and is a safer option compared to admission of employees to the unstable slope structures.

The Pyhäsalmi deposit is the deepest underground mine in Europe and at the end of its life cycle. Integration of high-resolution UAV data with satellite data will help to monitor slope integrity, both open pits and tailing ponds. The precise GNSS geolocation will ensure the re-user safety. The underground trials were related to tracking of mobile vehicles and personnel. Environmental monitoring and controlling may be enhanced remarkably with satellite data providing excellent long-term monitoring in the mine area. The underground GPS location was demonstrated in Pyhäsalmi 400 metres below ground level, making it usable for drone flight control and test use of commercial positioning software (e.g. Google maps). The results have raised a lot of industrial interest. The system can be applied in various underground scenarios, including people safety, asset management, and tunnel inspections.

The Trepca pilot in Kosovo aimed to evaluate the environmental risks of a closed mining area as well as to evaluate the potential for secondary raw material extraction of the remaining tailing areas. During the field trial the focus was on safety and

environmental monitoring of the tailings in Mitrovica, Kisnica & Graçanica, Zveçan, Kelmendi, Leposaviç, and on Acid Mine Drainage evaluation. Based on the project results, negative environmental and social impacts were discovered in the post closure area. Monitoring the acid drainage water through GoldenAI platform will be recommended for affordability and safety. In addition, the results show that there is potential for developing some tailing dumps through reprocessing the tailings since rare earth elements have been identified.

THE IMPACT OF GOLDENAI PLATFORM AND FIELD TRIAL RESULTS

The Goldeneye project use cases contribute to a positive impact on the EU economy and society in relation to access to raw materials in many ways: The Goldeneye-platform provides easy access to a data fusion portal offering a wide catalogue of artificial intelligence knowledge packs (AI KP) for application in exploration, mining operation, mining monitoring and post closure monitoring. It allows the fusion of different public and commercial satellite and drone imagery to European mining industry on one marketplace under one portal. The integrated AI KPs in combination with external tools (FUSE, advangeo 3D Prediction, FLAC 2D) and the data acquired using the newly developed sensors (drone-based electromagnetic measurements, active hyperspectral scanning) enable its users more precise mineral exploration targeting as well as identification of environmental and geotechnical risks and hazards during the mining operation and after its closure. The improved environmental monitoring helps to prevent mining-related accidents, and in the future, the tools developed in the project improve the valorisation of tailing areas helping to mitigate damage from mines.

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REFERENCES

Filchev, L., Pashova, L., Kolev, V. & Frye, S. 2018. Challenges and solutions for utilising Earth observations in the "Big Data" era," BigSkyEarth conference: AstroGeoInformatics, Tenerife, Spain, December 17–19, 2018.

Johnson, D. B. 2018. The evolution, current status, and future prospects of using biotechnologies in the mineral extraction and metal recovery sectors. Minerals 8(8), 343.

Li, H., Eksteen, J. & Oraby, E. 2018. Hydrometallurgical recovery of metals from waste printed circuit boards (WPCBs): Current status and perspectives – A review. Resources, Conservation and Recycling 139, 122–139.

MULTISCALE AND MULTI-SENSOR MAPPING FOR TAILINGS MANAGEMENT AND MINE FACE OPERATIONS: REVIEW AND PERSPECTIVES

by

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The interdependence of economic markets across European countries, as well as those between the European Union (EU) and external markets, create a delicate balance in the supply and demand for raw materials and manufactured products. Access to a range of raw materials such as minerals bearing Al, Au, Co, REE, Co or industrial aggregated is critical in key areas of the economy, creating a sustainable pathway to energy transition, as well as driving digital transformation. While alternative technologies, including recycling, are expected to contribute to the reduction in dependence on raw materials, a more immediate strategy for securing access to essential metals and minerals still relies on mining new resources. The rising demand in metals and minerals will inevitably coincide with mining and mineral processing and waste and environmental consequences. The global progress towards a clean energy future could substantially be slowed down and made more expensive when leaving these critical raw material needs and consequences unaddressed (IEA 2021). Concerns about mine waste further underscore the need for sustainable solutions. For instance, an estimated 14.4 billion tonnes of mining waste are created during the extraction of 5.6 billion tonnes of metallic/non-metallic ore (Ramani 2012). Right now, more than 4700 Mt of mining waste and 1200 Mt of tailings are deposited across the European Union (BRGM 2001). Acid mine drainage and environmental disasters emphasise the urgency of proper waste management and the safety of mining practices. Obtaining mining licences is going to increasingly depend on correct tailing management plans in the future, as stated in the Global Industry Standard on Tailings Management (ICMM 2020). Earth observation technologies – from the detailed mine face scale to site and regional scale – have high potential for optimal tailings management, improving operational efficiency of mining activities and helping to reduce energy and environmental footprints.

The M4Mining project is aiming to advance sustainable mining using integrated remote sensing data. The M4Mining project's overarching goal is to develop integrated remote sensing solutions for mining and tailing sites (Fig. 1). This includes real-time mapping, multi-sensor UAV infrastructure, best practices

establishment, closing resolution gaps, user-friendly interfaces, and applicable data analysis techniques. These objectives intend to enhance sustainable extraction, waste reduction, and environmental monitoring (Fig. 2).

The project's six core objectives are:

1) to empower decision makers with real-time mapping. In collaboration the mining industry, the project will create user-friendly, interoperable data products across spatial and temporal scales. This aids decision makers in achieving sustainable extraction and safe closure, bolstering productivity and selective extraction while minimising waste and contaminants.

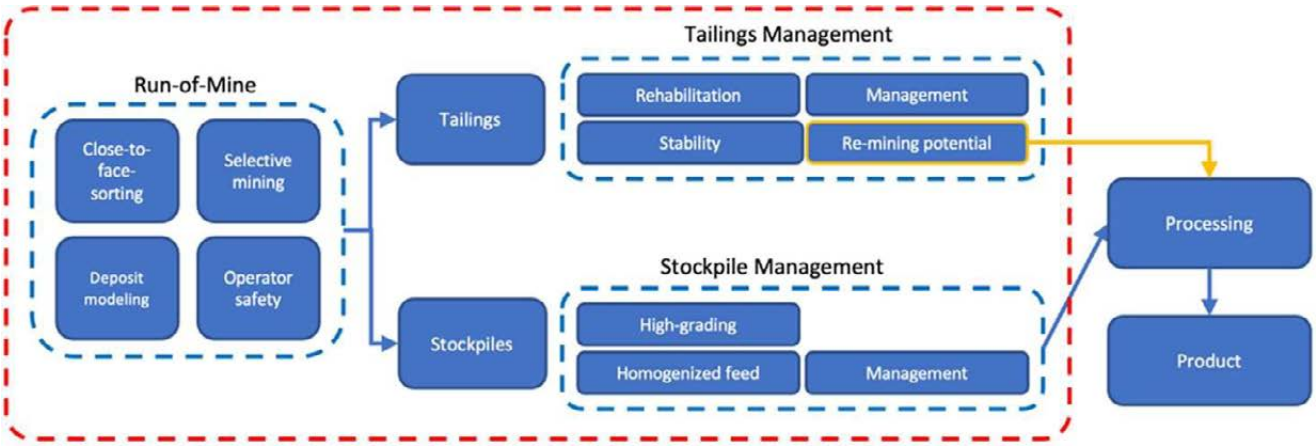

Fig. 1. The focus of the M4Mining project. Our solution aims to support the parts of the mining flow sheet marked in red: enabling an increased productivity, reduced tailings footprint, early waste rejection, reduced material re-handling, reduced erroneous allocation of material in waste or stockpiles, improved deposit modelling, increased re-mining, reduced feed variability, and a predictive tailings management.

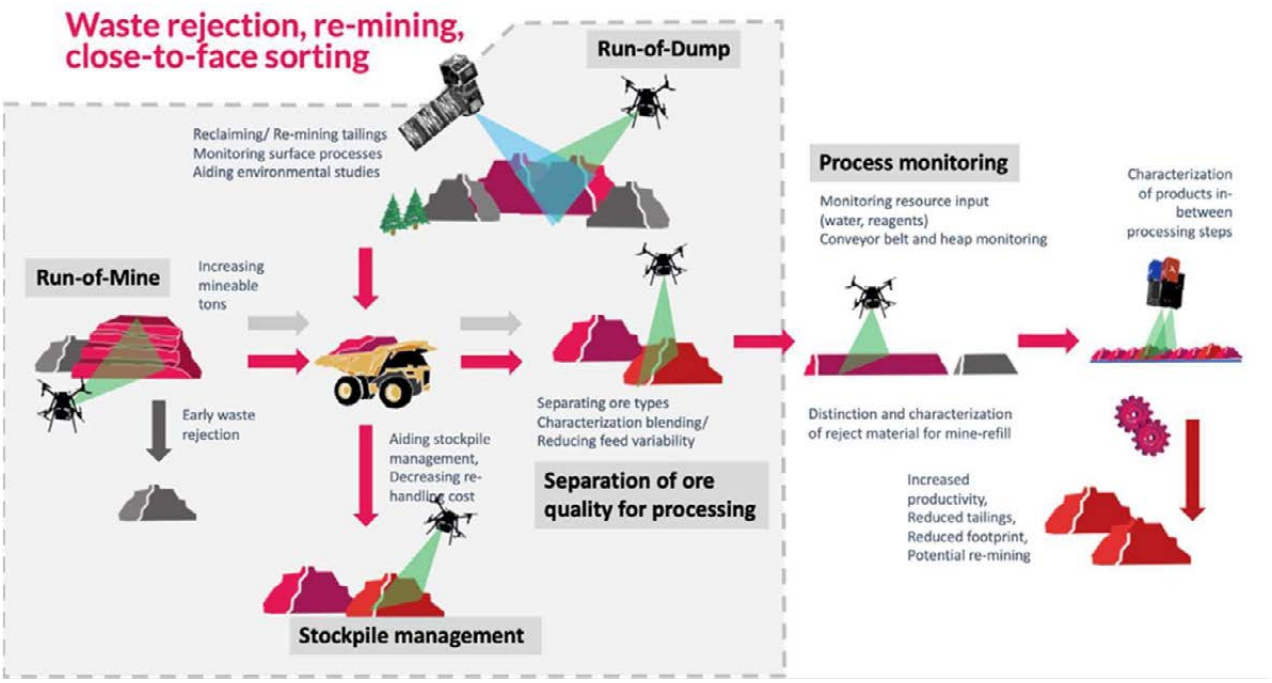

Fig. 2. The M4Mining project integration scope within the mining environment (grey box indicates project's focus area).

2) To develop robust UAV infrastructure by designing a specialised UAV platform integrated with hyperspectral imaging, 3D LIDAR, and inertial navigation systems. This platform enables real-time mapping of material distribution, monitoring of ore grade, and hazard evaluation. By utilising edge computing, the project facilitates interactive 3D visualisation. This combination of drone, payload, processing, and visualisation is key in opening novel time-critical applications of the technology in mine operations and environmental management.
3) To establish industry best practices by forming a Mineral Industry Advisory Board (MIAB) to standardise data and deploy UAV systems. Representation will be sought from mid-tier to major mining companies, Mining Equipment Technology Services companies and mine waste environmental & rehabilitation agencies. The MIAB will provide input on industry standardisation of (I) data and (II) safe deployment of octocopter UAV systems in active mine sites.
4) to bridge the temporal, resolution and scale gaps by addressing the disparity between satellite and UAV data resolution. Through interlinked approaches and usage of multi-sensor datasets, the scaling gap could be closed, enhancing sustainable extraction and closure monitoring. A key part of the proposed work is related to investigating the relationship between mine site scale, typically covered by satellite or nadir-looking drone imagery and outcrop scale of mine faces covered by high-resolution drone data.
5) To make the resulting data more accessible by simplifying interfaces for non-expert users. The project develops workflows for automated hyperspectral data processing, enabling quantitative mineralogical characterisation. User-friendly software interfaces provide ready-to-use maps for decision makers.
6) To innovate data analysis for hyperspectral imagery, studying the transferability of analysis models between scales and deploying spectral processing techniques to generate essential mineralogical information. The M4mining project will study the transferability and performance of developed processing and analysis models and methods between scales, including UAV data, EnMAP hyperspectral and Sentinel-2 and WorldView-3 multispectral satellite data, and approaches for upscaling spectroscopic-based mineral products across scales in mining environment.

Part of the current work of the M4Mining project is to provide an extensive overview of the current applications of hyperspectral and multispectral remote sensing data in mining operations, closure, and post-closure phases. A focus is set on the demand for these data products in mining, their scalability from UAV to satellite platforms, their impact on and integration within the mining industry, and the potential applications throughout the mine life cycle. We first provide an overview of the most important applications of spectral remote sensing data in the area of tailing monitoring and mining operations and then objectively compare data analysis methods documented in existing literature based on criteria such as accuracy, scalability, real-time processing potential, value to miners, and the alignment with current mining workflows.

The preliminary data processing algorithms under close consideration for integration into the "breeze" software by Prediktera AB include the following categories:

1. Spectral Indices and Band Ratios: Employing simple equations to compare intensity at different wavelengths.
2. Similarity Metrics: Comparing HSI spectra to reference spectra of known material types, for instance, through methods like Spectral Angle Mapper (SAM).

3. Machine Learning Models: Concentrating solely on spectral input, excluding spatial correlation. These models rely on labelled training data or existing spectral datasets for known mineral types. Examples include PLS, PLS-DA, Neural Networks, SVM, and Random Forests.
4. Unsupervised Classification and Clustering Techniques: Methods that identify naturally occurring groups of materials without requiring prior knowledge or training, such as K-Means clustering.
5. Statistical analysis techniques, including Principal Component Analysis (PCA) or Minimum Noise Fraction (MNF).

The software will facilitate the creation of personalised data processing workflows, allowing the application and interconnection of the methods.

In summary, the M4Mining initiative is expected to advance mining through integrated remote sensing data, bridging resolution gaps, empowering decision makers, and enhancing sustainable practices. The M4Mining project's ambitions perfectly align with the EU's raw material security and environmental sustainability goals. By harnessing advanced remote sensing technologies, the project strives to improve mining practices, ensuring a greener, more efficient, and accountable mining industry.

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REFERENCES

BRGM 2001. Management of mining, quarrying and ore-processing waste in the European Union. European Commission, Directorate-General Environment, ENV.E.3–Waste Management, BRGM/RP- 50319-FR. Available at: https://ec.europa.eu/environment/pdf/waste/studies/mining/0204finalreportbrgm.pdf. [Accessed 30.3.2022]

ICMM 2020. Global Industry Standard on Tailings Management. Available at: https://www.icmm.com/en-gb/guidance/environmental-stewardship/global-industry-standard-on-tailings-management. [Accessed 28.3.2022]

IEA 2021. The role of critical minerals in clean energy transitions – analysis, IEA 287. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions/executive-summary

Ramani, R. V. 2012. Surface mining technology: progress and prospects. Procedia Engineering 46, 9– 21. Available at: https://doi.org/10.1016/j.proeng.2012.09.440

ADVANCEMENT IN GEOPHYSICAL PEGMATITE EXPLORATION: A CASE STUDY FROM THE GREENPEG TEST SITE IN TYSFJORD, NORTHERN NORWAY

by

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Geophysical exploration for pegmatites remains challenging, owing to the generally weak geophysical signal caused by a low petrophysical contrast between pegmatite and wall rock. However, no published case studies have explored the petrophysical context of pegmatite deposits and their host rocks at depth. As a result, the geophysical approaches used in pegmatite exploration are typically chosen based on geological observations, experience from other ore deposits, or simply budget considerations. However, to make a reasonable decision on geophysical investigation at a specific site, petrophysical studies are rarely, if ever, done at an early stage of the exploration.

The EU Horizon 2020-funded project GREENPEG intends to close this knowledge gap by conducting extensive geological, geochemical, and geophysical studies for various pegmatites in various environments at three demonstration sites in Europe (Müller et al. 2022). We developed toolsets for cost-effective and sustainable exploration, specifically tailored to the various settings at the three demonstration sites. Our findings confirmed the significance of a thorough understanding of the genetic, structural, and lithological contexts of the local pegmatite for successful exploration at each demonstration site.

In this paper, we will focus on the geophysical exploration part and describe a multi-geophysical survey to test and evaluate the different geophysical methods and their combinations to find the best approach for successful data interpretation and identification of buried Nb-Y-F (NYF) pegmatites. Our field laboratory was the pegmatite quarry Jennyhaugen in Drag, Northern Norway, which is part of the GREENPEG demonstration site at Tysfjord.

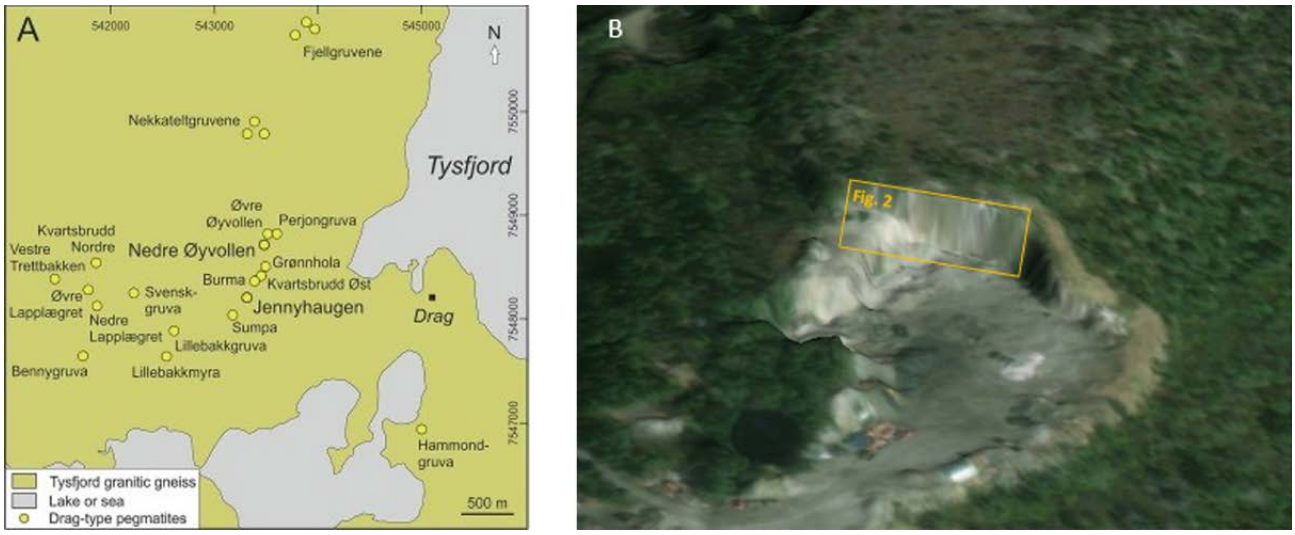

Fig. 1 a) Schematic geological map showing the cluster of the Drag-type pegmatites near the Drag village (from Zhou et al. 2023). b) Aerial view from SW of the Jennyhaugen with the quarry in the front and the continuation of the pegmatite towrds NE.

The Jennyhaugen pegmatite (Fig. 1) is located in the centre of the Drag pegmatite cluster and forms a broad, remarkable NE-SW lens-shaped ridge up to 40 m wide and at least 200 m long. Since the 1910s, the southwestern part of the ridge has been mined, forming a quarry with a 25-metre-high vertical rock wall at its northern end, where the pegmatite continues farther northeast.

The pegmatite is now exposed across its entire width in the Jennyhaugen quarry (Müller et al. 2017), providing a unique look into the geometry and boundaries of the pegmatite, the mineralogical zoning of the pegmatite, and the host rock, the Tysfjord granitic gneiss (Fig. 2). Based on the study of this outcrop, Zhou et al. (2023) conclude *the pegmatite [...] has a* [NE] *dip of ~70° and displays a strike parallel to the foliation of the granitic gneiss. The massive quartz core gradually changes into a wide blocky intermediate zone (a few to tens of metres thick). In the intermediate zone, quartz ribbons can be found in the light-pinkish K-feldspar masses (together with minor plagioclase) and show elongation parallel to the strike of the pegmatite body. [...] The wall zone consists of foliated aplite up to 5–10 m in width and is sharply contacting the foliated granitic gneiss.*

Fig. 2. The distribution of the Tysfjord granitic gneiss, wall rock and feldspar pegmatite with a quartz core zone (Zhoug et al. 2023).

On top of the ridge to the northeast of the rock wall, typical arctic vegetation with tiny trees, little soil cover, and peat bog overlays the bedrock. It does, however, outcrop in various places, showing the continuation of the pegmatite towards the NE along with the striking of the ridge, which is flanked on both sides by the Tysfjord granitic gneiss. Several granite outcrops near the ridge's core, however, indicate a split and possibly bisection of the pegmatite (Fig. 5). Furthermore, the Jennyhaugen pegmatite was extensively investigated by NGU during the 1970s, including a comprehensive drilling programme. The drill cores are still stored at the NGU drill core repository in Løkken, Mid Norway, and available for inspection. This contributes to an even more complete picture of the pegmatite distribution and interaction with the wall rock, making it ideal for testing different geophysical methods and their ability to map pegmatites.

The Petrophysical Database for European Pegmatites (Haase & Pohl 2022) and the Spectral Library of European Pegmatites (Cardoso-Fernandes et al. 2023) are two main outcomes of the GREENPEG so far, highlighting the relevance of these information for an efficient and cost-effective exploration process.

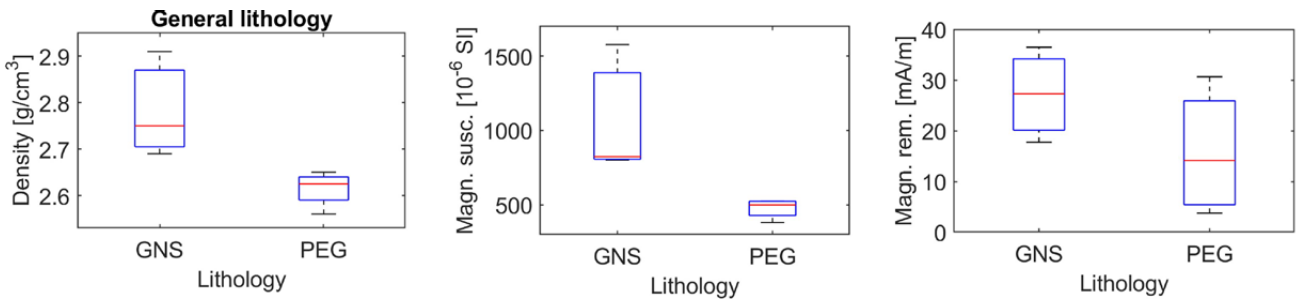

Fig. 3. Extraction from the GREENPEG petrophysical database for pegmatites for Jennyhaugen (Haase & Pohl 2022). The data show a petrophysical contrast in density and magnetisation between pegmatite (PEG) and the host rock (GNS).

For Jennyhaugen, we derived petrophysical data for the various lithologies from hand specimens, drill cores, and borehole logging, providing an important hint of the existing petrophysical contrast between wall rock, pegmatites, and quartz and defining which geophysical methodologies aim to be most successful for imaging the different units (Fig. 3). NYF pegmatites often have a distinct halo enriched with thorium (Th), uranium (U), and potassium (K). The pegmatite in Jennyhaugen is no exception, and the halo there has been studied in detail (Haoyang Zhou pers. comm.), revealing a width of the halo of up to 20 m. Consequently, in addition to geophysical approaches, gamma spectrometry was used as an additional prospecting tool (Fig. 4).

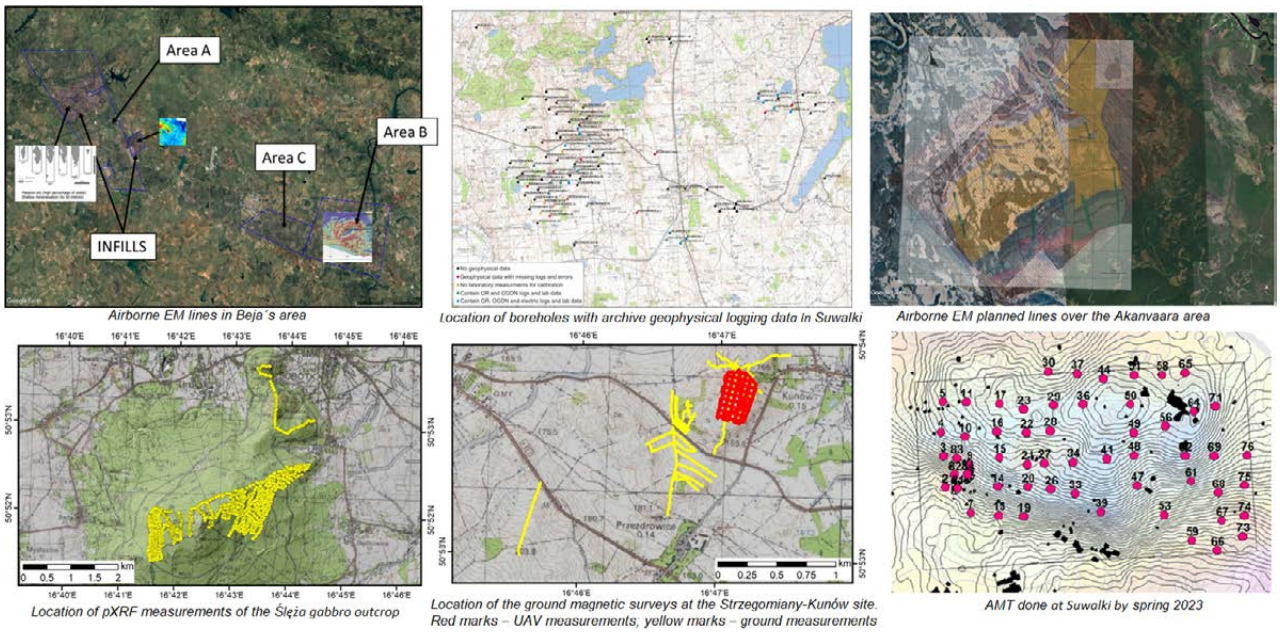

Fig. 4. Total counts from ground borne gamma spectrometry on Jennyhaugen indicate the edges of the pegmatite and a good fit with the predicted pegmatite outline from geological mapping. Thick overburden can mask the halo as it is seen in the central part of the survey (dark red) correlating with thick peat bog.

Based on the petrophysical study corresponding geophysical datasets were acquired along or near the same a historical prospect drilling profile (Fig. 5). The different datasets address different subsurface petrophysical parameters and provide in combination a detailed and well constrained interpretation of the geology and the location of prospective pegmatites.

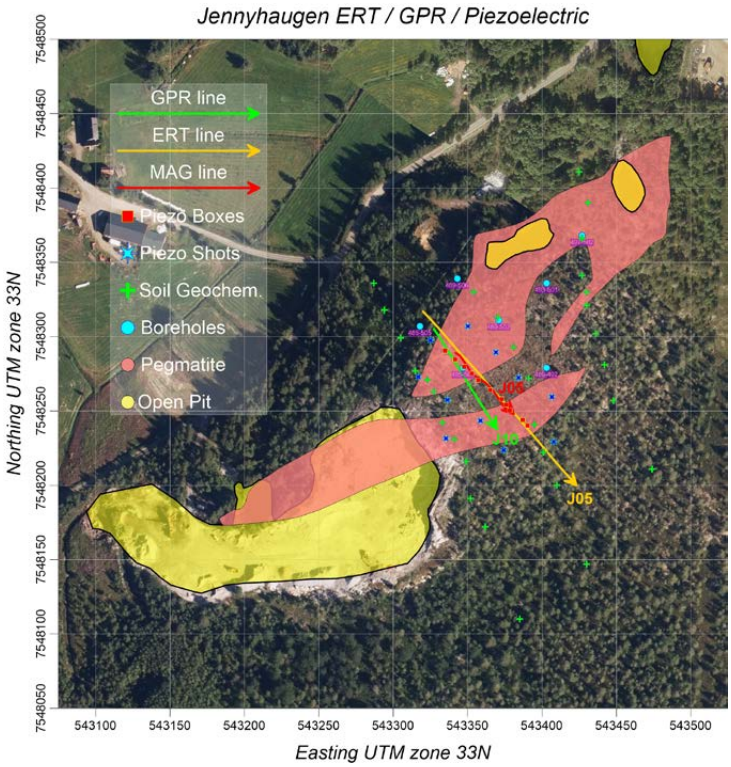

Fig. 5. Overview map for the location of the various data used in the presented integrated interpretation study at Jennyhaugen. The data are all along or near by the same prospect drilling profile underlain by the geological interpretation of the extension of pegmatite bodies (red).

We distinguish between technologies that offer lateral changes in a petrophysical parameter (e.g., magnetics) along the profile and 2D imaging of the subsurface (e.g., GPR). In the presented case, ground magnetics, piezoelectric, GPR, and ERT are contrasted (Fig. 6), with the interpretation of the latter two backed by logged borehole lithology. The SE margin of the pegmatite exposed under the overburden was confirmed by gamma ray. Gravity was also examined using the observed petrophysical contrast (Fig. 3), but while the data suggested a slight anomaly, the changes were not significant enough for modelling.

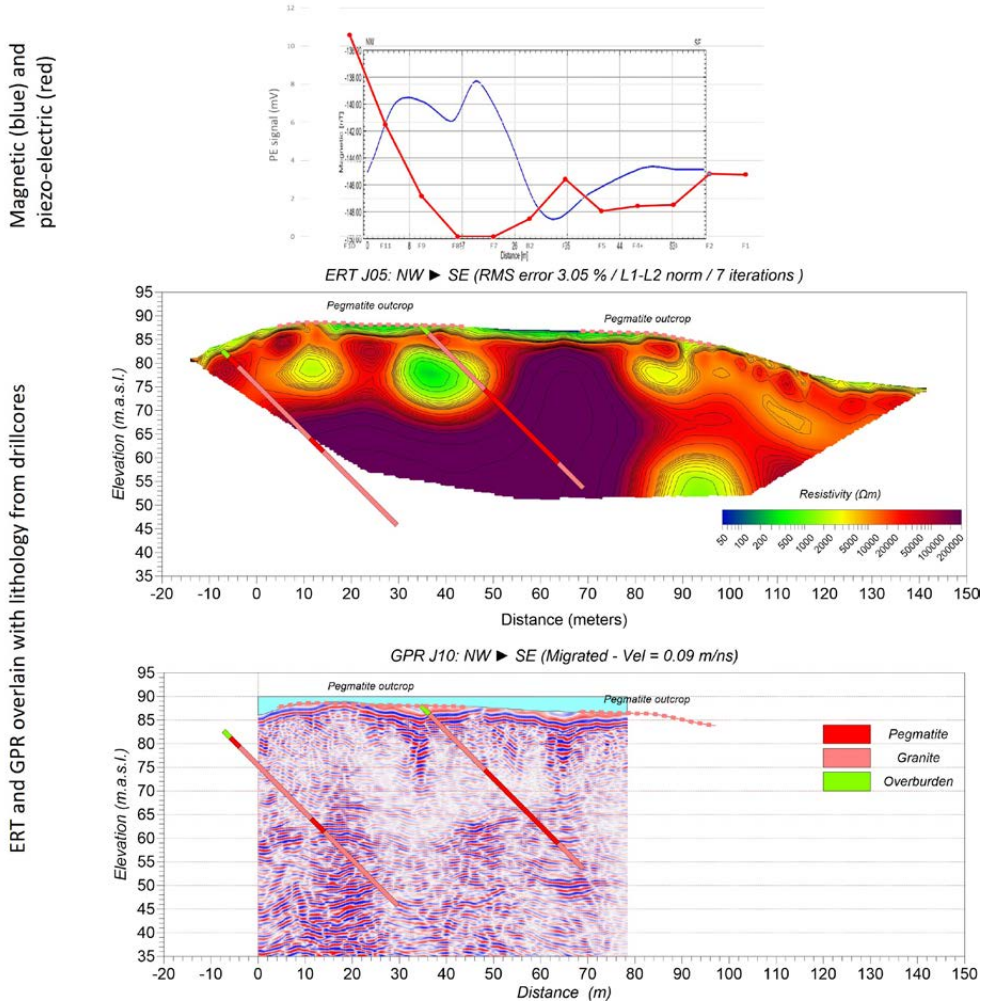

Fig. 6. Complementary plot of different geophysical profile data along the same line. Lithological data from boreholes are used for further constrain.

Magnetic and piezoelectric (PE) data show an inverse picture, with the magnetic signal being strong when the piezoelectric signal is low and vice versa. This is consistent with our petrophysical investigation from this location, which showed low magnetic pegmatite (Fig. 3) and significant quartz piezo activity. As a result, the magnetic low and PE peak in the centre of the profile imply a pegmatite body beneath, whereas magnetic highs on both flanks indicate a granitic gneiss-dominated subsurface. However, except for one minimum, the PE signal exhibits an intermediate response, indicating the presence of potentially deeper-seated pegmatite deposits. The PE maximum at the NW end of the profile coincides with the end of a magnetic high, implying that shallow-seated pegmatite bodies are nearby.

When compared with the image-giving methodologies GPR and ERT, we can find a fairly good correlation between magnetic low, PE peak, high ERT resistivity, and low GPR amplitude. Boreholes confirm that high resistivity and low GPR amplitude coincide with logged pegmatite, allowing us to conclude that in this setting with NYF pegmatites hosted in the Tysfjord granitic gneiss, the applied methods can identify buried pegmatites and, when combined, even contribute to a refined understanding of pegmatite bodies' setting and shape.

However, some issues that challenge the obvious interpretation here must be addressed. Noticeable, high resistivity and drill logs do not fit exactly, which is most likely owing to the ERT's limited resolution. Magnetic and PE can contribute to a more detailed interpretation in particular when borehole information is missing. Finally, because PE is one of the new tools developed in GREENPEG, it is worth highlighting that we were able to map a ca. 5-10 m deep buried pegmatite using the PE method.

REFERENCES

Cardoso-Fernandes, J., Santos, D., Rodrigues de Almeida, C., Lima, A., Teodoro, A. C. & GREENPEG project team 2023. Spectral Library of European Pegmatites, Pegmatite Minerals and Pegmatite Host-Rocks – the GREENPEG project database, Earth System Science Data 15, 3111–3129. Available at: https://doi.org/10.5194/essd-15-3111-2023

Haase, C. & Pohl, C. M. 2022. Petrophysical Database for European Pegmatite Exploration –EuroPeg. Minerals 12(12), 1498. Available at: https://doi.org/10.3390/min12121498

Müller, A., Reimer, W., Wall, F., Williamson, B., Menuge, J., Brönner, M., Haase, C., Brauch, K., Pohl, C., Lima, A., Teodoro, A., Cardoso-Fernandes, J., Roda-Robles, E. Harrop, J., Smith, K., Wanke, D., Unterweissacher, T., Hopfner, M., Schröder, M., Clifford, B., Moutela, P., Lloret, C., Ranza, L. & Rausa, A. 2022. GREENPEG – Exploration for Pegmatite Minerals to Feed the Energy Transition: First Steps towards the Green Stone Age. London: Geological Society 526, 193–218.

Müller, A., Romer, R. L. & Pedersen, R.-B. 2017. The Sveconorwegian Pegmatite Province – thousands of pegmatites without parental granites. Canadian Mineralogist 55, 283–315. Available at: https://doi.org/10.3749/canmin.1600075

Zhou, H., Müller, A. & Berndt, J. 2023. Quartz chemistry fingerprints melt evolution and metamorphic modifications in high-purity quartz deposits. Geochimica et Cosmochimica Acta 356, 2023, 179–195. Available at: https://doi.org/10.1016/j.gca.2023.07.015

ENVIRONMENTAL, SOCIAL AND GOVERNANCE (ESG) IN MINERAL EXPLORATION – WHAT DOES IT LOOK LIKE IN PRACTICE?

by

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Mining is a divisive word: it immediately recalls destruction, conflict, and negative impacts on people and planet. Renewable energy and electric vehicles, on the other hand, bring images of a hopeful, clean future with positive impacts on nature and communities. The two are diametrically opposing but simultaneously inextricably linked; we cannot maintain our current lifestyles in future without mining. There is also clear trust issue between mining companies, governments, local populations, and consumers. To bridge these seemingly unbreachable gaps, the concept of environmental, social and governance (ESG) is a tool with which mining can pull its collective socks up and ensure raw materials extracted for 'green' technology is, itself, 'green'. Although the term is a relatively recent phenomenon, the ideas behind it are ancient and stem from humanity's deep connection to both the natural world and other people. ESG is also not specific to raw materials extraction and use, but it has a particularly intimate link due to the obvious physical connection between the ore extracted from the rocks and the overlying and adjacent environment, ecosystems, and local populations. This paper looks into the specific application of ESG concepts focussing on mineral exploration projects prior to mine development. Successful applications for mining permits/licences and associated environmental and social approvals are declining in many developed countries, who contemporaneously are ramping up efforts to secure sources of critical raw materials. In addition, timescales from discovery to development has been increasing rapidly, with a time-lag of 20 years not uncommon; something must give.

The term sustainability is linked to ESG and frequently used in place of it, but it has a different purpose. Sustainability relates to the long-term viability of a process, a business, or a product in three main areas – environmental, social and economic – often referred to as the 'triple-bottom line'. For example, the 'sustainability' of the cement-production process, the 'sustainability' of an energy company, or a 'sustainable' toothbrush product. ESG can equally be used in the context of a process, a company, a product, a project, or a whole supply chain. ESG does not have specific requirements or levels of attainment, it is simply a collective term for communicating the relevant and material context of a product/process/company to stakeholders. A project cannot be 'ESG-compliant' or have 'good' or

'bad' ESG; it is simply stating the facts for stakeholders to digest and discuss. The fundamental difference between ESG and sustainability is transparency.

In the context of mineral exploration and mining, ESG has fast become a buzz word necessary to attract finance and gain stakeholder approval particularly for greenfield exploration projects. Additional emphasis on environmental, social and governance issues can only be a good thing in theory; however, caution must be applied when making judgements on projects or companies based on ESG ratings or scores. Although helpful when making comparisons and deciding on which project to back, an exploration property is entirely dependent on the physical location, and thus it is clear that some aspects are incomparable, and context must be kept in perspective. A good example is comparing greenfield nickel deposits: a hard-rock (sulphide) deposit hosted in a remote, sparsely populated part of the Arctic has a significantly different context to a soft-rock (laterite) deposit hosted in a densely populated, biodiversity-rich part of equatorial Southeast Asia. It is not right to single-out specific differences in natural environment, communities, social perceptions, government regime, economics, human rights, corruption, biodiversity, ecosystems, for example. A pragmatic, holistic and balanced approach must be taken before making decisions on ESG aspects of projects.

Fig. 1. Environmental, social and governance in mineral projects.

Before you start your ESG or sustainability assessment, it is logical to first ask the question: what does a model mine look like? It must be designed with as low a negative impact and as high a positive impact on environment and communities as possible. First and foremost, it should benefit local communities and adhere to national and regional regulation, but it should also benefit global society – the commons. If it does not, then should it be considered viable? Just because something is economically viable and will benefit a small group of individuals, should it be permitted?

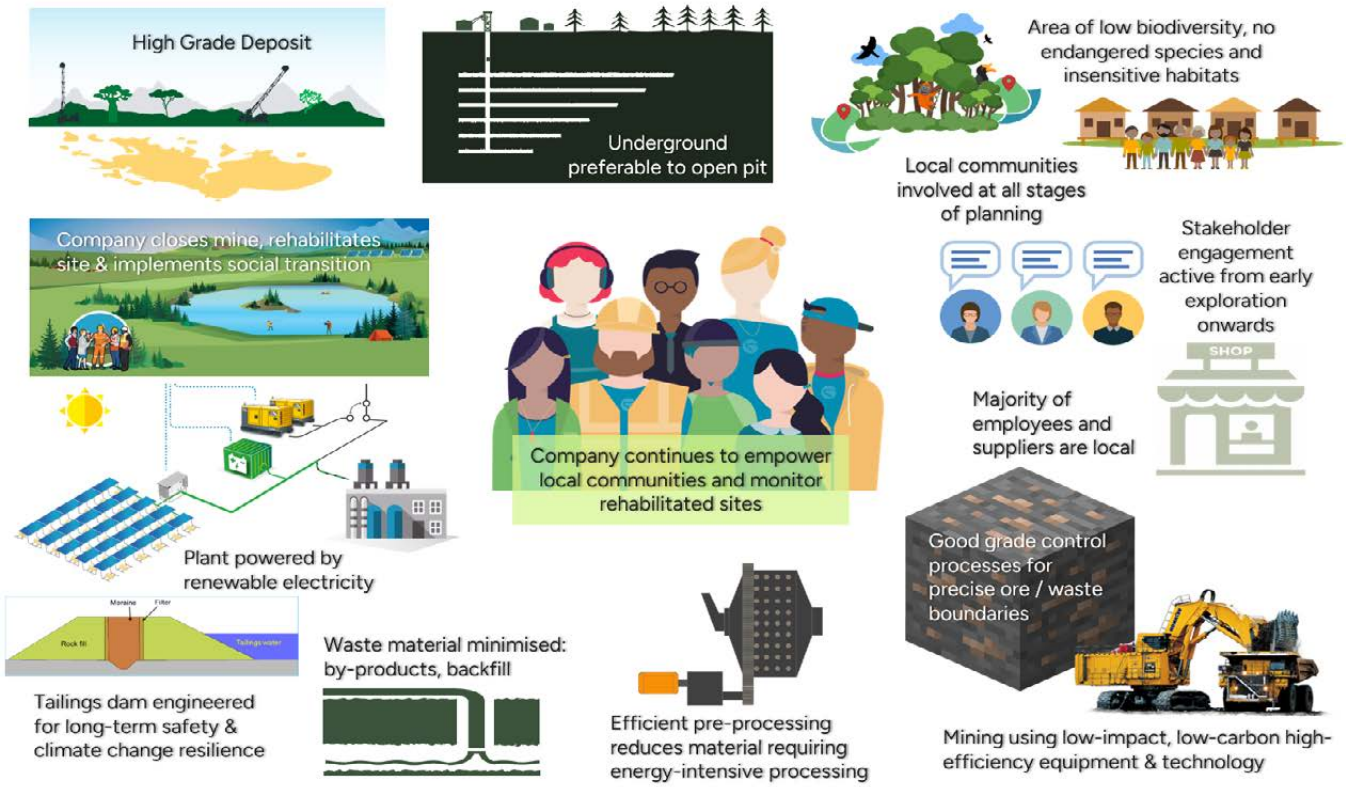

Fig. 2. The Model Mine.

The United Nations Environment Programme (UNEP) coined a new term in 2020 as an extension to the well-used phrase social licence to operate (SLO): the sustainable development licence to operate (SDLO) as described in IRP (2020). The concept of SDLO revolves around multi-stakeholder consensus of acceptance for a specific project based on the fundamentals of the UN's sustainable development goals (UNSDG, https://sdgs.un.org/goals). Essentially a project needs to demonstrate it meets the requirements of the UNSDGs for it to be viable. It also sets out a '*framework for coordinated and cooperative action to enhance the contribution of the extractive sector to the UNSDGs*' (IRP 2020).

Fig. 3. Sustainable Development Licence to Operate.

ESG is a broad and complex concept to comprehend, particularly at the exploration stage when there are so many unknowns. A good place to start is at the end: by remembering that a mine is a temporary land use and one day will close. This is such a fundamental statement that is overlooked too often and can easily result in conflict and irreparable damage to people and planet. For this, when assessing a project or company on their ESG credentials it is necessary to look at the mine plan and schedule. This will give a good indication of the mining rate (quantity of ore extracted on a monthly/annual basis usually), mining method (examples include underground block cave, open pit, surface strip mine, in-situ leach, dredging), processing type (e.g. crushing, smelting, electrolysis, acid leach), the ore grade (and conversely the quantity of waste rock and process residue/tailings) and also life-of-mine (how long the ore will be mined for). All these aspects will provide an understanding of the scale of the project including distances between the mine and key infrastructure, such as tailings disposal facility and port. It will also provide an understanding of how long the mine and associated infrastructure will be required for and when it can be transferred back to a different land use. This is the concept of closure and needs to be considered at the earliest onset of project development. The locally and regionally affected people must be able to conceptualise the future of their land to give their consent (whether that is a pre-requisite for project approval or not is a separate issue). But without having a closure plan and vision, it is not possible to communicate the whole story and gaining SLO or SLDO will be difficult.

Probably the most important part of ESG assessment for a mineral exploration project is the licencing or permitting. This is also one of the key aspects of Mineral Resource and Ore Reserve (MRMR) reporting of mineral projects relating to ESG. International MRMR reporting frameworks, guided by the umbrella

organisation CRIRSCO (Committee for Mineral Reserves International Reporting Standards, https://www.crirsco.com/) and including the Australian JORC, South African SAMREC and European PERC codes/standards, all require reporting of ESG criteria. Currently this focusses strongly on the requirement to demonstrate 'reasonable prospects for economic extraction' (RPEE) for Mineral Resources or demonstrating project viability including ESG 'modifying factors' to convert Resources to Reserves. If a project is unlikely to get mining and/or environmental & social permits to operate – or it is expected to take a significant period of time to receive approvals – then it can it be considered as a viable project?

Climate change is an urgent and pressing issue that forms a fundamental part of any ESG assessment. A company must demonstrate mitigation strategies – including reductions in greenhouse gas (GHG) emissions or ambitions for net-zero – from day one of planned operation. These strategies must incorporate science-based targets into any development schedule in-line with the Paris Agreement (UNFCCC 2015, https://unfccc.int/process-and-meetings/the-paris-agreement) and any other commitments the host country is party to. Climate change adaptation strategies are an equally as urgent consideration, with climate change predictions built into the engineering and design of a project from the start. This is particularly urgent in low-lying areas prone to flooding, water-stressed regions, regions of permafrost or freeze-thaw cycles. Attention must be paid to the potential longevity of the project – a 10-year mine life presents significantly different threats that a 100-year mine life. Caution must also be taken when technologies are planned to be implemented that have yet to be developed or successfully trialled for similar projects. For example, electrification of mining fleet – haul trucks, excavators etc. – where battery electric and hydrogen-based alternatives to diesel-powered equipment exist. But again, it is context-specific and such grand intentions may not be viable for a specific mine: for example due to variations in scale, geographic location, gradient/terrain, power availability, energy mix (fossil fuel to renewable ratio), or even project economics.

Negative impacts of a project on the receiving local environment and ecosystems must be minimised or eradicated where possible. Many companies are now starting with a net-positive vision, where successful completion of the project would result in a higher level of environmental performance than pre-mining conditions. This could be in the form of improved biodiversity, water quality, air quality, soil health, forest density or a number of other metrics. This must also be extended to local communities with a particular focus on vulnerable groups, such as traditional and indigenous peoples. The impact of a modern mine on a traditional way of life may not be possible to understand as an outsider part of mainstream society, which is why significant effort must be taken to first understand their perspectives and potential issues then work collaboratively to avoid, remove, mitigate, reduce or (worst case scenario) compensate for any negative impacts (mitigation hierarchy).

Despite the many challenges facing a modern mine from progressing from exploration through construction to mining, modern society urgently requires new mines to be built to ensure we have the raw materials for the energy transition. They must be built, operated and closed in a way that optimises opportunities for local communities (including vulnerable parts of society), minimises negative impacts on local environment and society and works towards the goals of UN sustainable development goals.

REFERENCES

IRP 2020. Mineral Resource Governance in the 21st Century: Gearing extractive industries towards sustainable development. In: Ayuk, E. T., Pedro, A. M., Ekins, P., Gatune, J., Milligan, B., Oberle B., Christmann, P., Ali, S., Kumar, S. V, Bringezu, S., Acquatella, J., Bernaudat, L., Bodouroglou, C., Brooks, S., Buergi Bonanomi, E., Clement, J., Collins, N., Davis, K., Davy, A., Dawkins, K., Dom, A., Eslamishoar, F., Franks, D., Hamor, T., Jensen, D., Lahiri-Dutt, K., Petersen, I. & Sanders, A. R. D. A Report by the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

UNFCCC 2015. Paris Agreement. Available at: https://unfccc.int/sites/default/files/english_paris_agreement.pdf

EDUCATION, SOCIAL TRANSFORMATION, AND GLOBAL CITIZENSHIP: DEBATES, PATHS AND MEANING OF THE GREEN DEAL

by

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The European Green Deal (European Union 2020) requires resources in the form of humans and minerals to achieve its intent. Resistance to mining projects within Europe presents a huge challenge in terms of restricting access to Critical Minerals. How can the Europe achieve its aims without addressing its resource requirements and how can such requirements ever be regarded as acceptable? Does critical thinking and deliberative dialogue have a role in resolving this challenge?

The Horizon Europe research project, VECTOR, is building on the research findings from a Horizon 2020 Project INFACT, to further expand knowledge and research into use of minimally invasive geoscientific exploration methods. We are also continuing the journey to determine, understand and address many of the social challenges related to mineral exploration and mining in Europe. One social challenge is "how and what information is made available, in what form and how to enable more reliably-informed decision making".

We map the synergies and complementary objectives of the European Green Deal and the Sustainable Development Goals (SDGs) (United Nations 2015) with a focus on their mutual reinforcement, to provide a comprehensive framework for addressing climate change, environmental degradation, social inequalities, and promoting sustainable development both within the European Union and globally.

Education is also a focus – how it is integrated into the EGD framework, with an intent to build a more environmentally conscious and capable society to tackle climate and environmental challenges effectively. The role of education in promoting environmental and social justice and activism among young people is explored, focussing on the global education movements that seek to foster a sense of responsibility for the planet's future. We then raise the question: How then should mineral extraction and use, as probably one of the most contentious global challenges of the EGD, be addressed?

Based on a premise that critical thinking, inspired by thinkers like Habermas and Freire, provides a pathway for understanding complex global challenges, including the responsible management of critical minerals and that global education plays a key role in raising awareness about these issues and fostering informed global citizens who can engage in public discourse (Bourn 2021, Davies & Pike 2008, Fazio 2020, Scheunfplug 2008). Our research is on their collective ability to address the need for informed and inclusive discussions about sustainable

development, environmental protection, and the responsible sourcing and use of critical resources like minerals, all of which are essential for addressing the pressing challenges of our time.

Participatory Action Learning and Action Research (PALAR) is an approach that encourages active participation, collaboration, and learning within communities, making it particularly relevant to sustainability and green initiatives (Wood 2019). We are using PALAR as our research approach to engage and foster collaboration across three respective Communities of Practice (CoPs), each comprised of policymakers, scientists, and teachers from Ireland Bulgaria and Italy, engaging them in a participatory and action-oriented approach to explore aspects of the green deal and sustainable development.

The research is framed by Nature of Science (NOS) principles (Allchin 2011) combined with Paulo Freire's "Pedagogy of Hope" (2004), a holistic approach to education that encourages critical thinking, empowerment, and social transformation. Together, combined they encourage collaboration so that decisions are based on sound scientific principles, open dialogue, ethical considerations, and a commitment to sustainability and social acceptance.

Such an approach promotes an understanding of how science works, including its limitations, uncertainties, and the role of evidence. In a multi-country research project, this fosters epistemological awareness among both researchers and stakeholders and will lead to more informed and critical thinking about scientific findings. Emphasising the ethical aspects of scientific research, such as responsible conduct, transparency, and ethical decision-making and incorporating ethical discussions into research, can help ensure that projects in the EU adhere to high ethical standards.

By engaging in critical thinking, teachers and educators are working together, within their national CoPs and also across the wider VECTOR Professional Learning Community to assess the potential of critical thinking as a means to bridging the impasse between need for minerals and the acceptability of their extraction in Europe.

The challenges surrounding mining in Europe, including concerns related to the environment, communities, and sustainability, require thoughtful and informed decision-making. Critical thinking can be leveraged to address a number of key issues. It encourages a thorough examination of the trade-offs involved in mineral extraction. Critical thinking is in short, a valuable tool for addressing the challenges associated with mineral extraction in Europe. It promotes a holistic and informed approach that considers the full spectrum of economic, environmental, social, and ethical factors involved.

Enabling such discussion and critical enquiry is enabling teachers as educators to assess the necessity of certain minerals for various industries and technologies while considering their environmental and social impacts, in turn leading to more balanced and informed decisions on which minerals to extract and how to do so responsibly.

Evaluating alternative approaches to meeting mineral demands, can be used to critique exploration of the viability of recycling, urban mining (retrieving metals from existing infrastructure), and exploring substitute materials and possible help identify opportunities to reduce the need for new mining operations.

Drawing on the potential of fostering an open mind to solving problems is likely to lead to more rigorous assessment of the potential environmental and social consequences of mining projects. Such an inclusive approach enables diverse perspectives and concerns to be considered, fostering dialogue, consensus-building and the promotion of transparency. Through PALAR's feedback loops continuous learning and adjustment are encouraged so that the CoPs can adapt their methods

and approaches based on input and evolving project dynamics, enhancing the research's relevance and effectiveness. Recognising local knowledge as important in an empowering process for participants, a very important aspect of the wider Horizon Europe project framework.

Contextualising scientific knowledge within its historical, cultural, and social context is particularly relevant within our research as it supports the bridging of cultural differences and facilitate cross-border collaboration. By combining approaches in a multi-country research project we are seeking to create a collaborative and socially responsible research environment. This approach is likely to result in research outcomes that are not only scientifically rigorous but also relevant, ethical, and applicable to the diverse contexts and needs of EU member states. Additionally, it can foster stronger partnerships between researchers, stakeholders, and the public, promoting a culture of scientific literacy and informed decision-making.

Building teachers competencies and confidence to convey complex scientific ideas more effectively to their learners. Applying critical theories and pedagogies of Habermas and Freire to drive critical thinking and guide learners in making informed decisions about personal, local, and global issues (MacCallum 2012, MacCallum et al. 2022), with a scientific foundation is invaluable for fostering environmental stewardship, promoting sustainability.

Our intent is to develop a pedagogical framework to prepare learners to be informed, responsible citizens who can address the complex challenges facing society.

Keywords: Critical thinking, Nature of Science, Green Deal, minerals, Global Citizenship, Pedagogy of Hope

REFERENCES

Allchin, D. 2011. Evaluating knowledge of the nature of (whole) science. Science Education 95, 918–942.

Bourn, D. 2021. 'Pedagogy of hope: global learning and the future of education'. International Journal of Development Education and Global Learning 13 (2), 65–78. Available at: https://doi.org/10.14324/IJDEGL.13.2.01

Davies, L. & Pike, G. 2008. Global citizenship education. In: Lewin, R. (ed.) Handbook of practice and research in study abroad: Higher education and the quest for global citizenship. Routledge and Association of American Colleges and Universities, 61–78.

European Union 2020. The European Green Deal. [Online]. Available at: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Fazio, X. 2020. Reorienting curriculum for the Anthropocene. UNESCO Futures of Education Ideas LAB.

Freire, P. 2004. Pedagogy of Hope. New York: Continuum 2004, 8.

MacCallum, C. 2012. What is the role of education and or learning in developing an equitable global society, economy and sustainable environment? London: Development education research centre IOE, UCL.

MacCallum, C. Mkubwa, S., Maslin, R. & Shone, N. 2022. Global citizenship education in practice: A transformative approach to global learning in Zanzibar. Prospects 2022. Available at: https://doi.org/10.1007/s11125-022-09600-1

Scheunpflug, A. 2008. Why Global Learning and Global Education? An educational approach influenced by the perspectives of Immanuel Kant. In: Bourn, D. (ed.) Development Education: Debates and Dialogue. London: Institute of Education.

United Nations 2015. Sustainable Development Goals. [Online]. Available at: https://sdgs.un.org/goals. [Accessed 1.3.2023]

Wood, L. 2019. "PALAR: Participatory Action Learning and Action Research for Community Engagement". In: Zuber-Skerritt, O. & Wood, L. (eds) Action Learning and Action Research: Genres and Approaches. Bingley: Emerald Publishing Limited, 193–206. Available at: https://doi.org/10.1108/978-1-78769-537-520191017

GOOD PRACTICES FOR EXTRACTIVE ACTIVITY IN NATURA 2000 AREAS, FIRST STEPS

by

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INTRODUCTION

CIRAN (CrItical RAw materials extraction in enviroNmentally protected areas) Grant Agreement No. 101091483 of the European Union's Horizon Europe research and innovation programme, faces the challenge to reconciliate different societal objectives, such as maintaining resilient raw material supplies and preserving nature and cultural values in the EU. The need to secure critical raw material availability at EU level might determine in future years increase of mining activity in the European countries for certain minerals previously not mined. The project considers the policy and social framework as well as the practices adopted to operate in protected areas and evaluates the extent to which Critical Raw Materials (CRM) may or do occur in environmentally protected areas.

The knowledge of mineral resources varies from country to country, which might be also an indicator of the effort put in by different countries in mapping national mineral resources. The data have been collected and unified under a common classification system at a European level due to several relevant projects in the last few years. At the same time, the EU is densely populated, rich in cultural heritage and increasingly improving its habitat area network and areas of environmental or ecological value. Information on protected areas is well defined and easily accessible.

Accessible EU data on mineralisation at the moment are not to really sufficient to scope possible future conflicts of land use, but might give an idea of the extent of the problem. The methodology of the scoping study is shown in Nikolas Ovaskainen presentation.

GOOD PRACTICE CASES

Even though mining activities have an image of impacting greatly the environment and society due to some mining company's past behaviour, there are many examples of good environmental performance. N2K Group EEIG & IEEP (2019) show examples of extractive activities, mainly aggregate pits and hard-rock quarries, that operate near or within Natura 2000 areas. Some examples are: Limestone open quarries in Skôvde (Sweden), Santarem and Setubal (Portugal), and the sand and gravel pit Soto Pajares to the southeast of Madrid (Spain).

In some cases, extraction activities actually have even improved the diversification of the habitats, as for instance in Needingworth quarry in Cambridgeshire, one of the largest UK sand and gravel pit. The CIRAN project studies cases, where exploitation and extractive operations for CRM have been successfully developed near protected areas. They cover different stages of the life cycle, were developed within diverse policy frameworks, and show a set of protected ecosystems. The list of sites addressed in the project is shown in Table 1.

Cases studies aim to demonstrate the conditions to formulate systemic good practices at the permitting stage. Spatial, mineral resources and environmental governance as well as societal aspects are highlighted in the case studies to evaluate the alignment of sectoral policies and regulations at the EU and Member State (MS) level. Good practice aspects and enablers are identified.

Good practice aspects for mining in Natura 2000 areas have seen stakeholder cooperation at very early stages and are not restricted to regulatory procedures, but involve dialogues among actors, adoption of technologies that minimise impacts. This is supported by thorough impact assessments, mitigation actions, and remediation plans that support biodiversity and ecological values.

Some examples of non-destructive technologies adopted to perform exploration in Finnish cases included drones (UAVs), biogeochemistry from plant samples, sampling of spruce transpired fluids and snow, novel electromagnetic (EM) survey system on UAVs, field electrochemical probe instrument, portable XRF, mapping of the vegetation type and the analysis of vegetation change over time, Full Tensor Magnetic Gradiometry (FTMG), and closed-circuit drilling systems. During the permitting process, emission limits have been set and direction given for performing the operations minimising their impacts. The Finnish cases are shown in the presentation by Toni Eerola "Mining and mineral exploration projects within the Natura 2000 areas in arctic Finland".

The best practice procedures are then discussed and validated through the participation of citizen groups from five different EU communities in co-creation processes through focus groups and consultations. Recommendations for streamlining resource management policymaking will then be elaborated.

Table 1. Case studies analysed in CIRAN project that showed good practice operating in or near environmental protected sites.

Project/mining method/ resource	Town/country	Nature protection regime	Mining Stage
AA Sakatti Mining Oy / N/A / Cu, Ni, PGE-group metals.	Sodankylä, Finland	Natura 2000	Exploration
Blackstairs Lithium / N/A / lithium-bearing pegmatites and aplites.	Wicklow/ Carlow, Ireland	EU designation (SAC), National (natural heritage area)	Exploration
Emili: Beauvoir Lithium Mining Project Exploitation de Mica Lithinifere par Imerys (EMILI)	France	ZNIEFF (Zone Naturelle d'Intérêt Écologique, Faunistique et Floristique) – designated 2011 SAC (Special Area of Conservation) – designated 2013	Exploration Planning & Design
Mawson Resources / N/A / gold, copper	Ylitornio/Rovaniemi Finland	Natura 2000	Exploration/opening
Nussir ASA / underground / copper, gold, silver.	Hammerfest, Norway	Seiland National Park	Opening/active
Neves Corvo/underground / copper, zinc and lead.	South Portugal	Area covered by the Birds Directive and the Habitats Directive	Active
Serra Candeeiros regional case / dual / limestones.	Leiria, Portugal	National Natural Park. Extraction of dimension stones and industrial minerals	Active (≥380 quarries, 770ha)
Monte Tondo / dual / gypsum.	Emilia-Romagna, Italy	Natural park - UNESCO heritage candidate	Active/ under new assessment
Alligator river / open pit / uranium.	Northern Territory, Australia	Kakadu National Park (World Heritage site RAMSAR conv.)	Rehabilitation
Project/mining method/ resource	Town/country	Nature protection regime	Mining Stage
Northern Sweden regional case / N/A / Polymetallic.	Västerbotten/ Norrbotten, Sweden	Permitting in and adjacent to protected areas	Exploration/opening
Mittersill / underground / tungsten.	Salzburg, Austria	Adjacent to the National Park "Hohe Tauern"	Active
Woodsmith mine / underground /potash and polyhalite.	North Yorkshire, England	National Natural Park	Active
Redmoor / underground / tin-tungsten	Cornwall, UK	UNESCO cultural heritage area	Re-opening/exploration
Barruecopardo / open pit / tungsten.	Castilla y Leon, Spain	Natura 2000	Re-opening
Hemerdon Tungsten / open pit / tungsten-tin.	Devon, UK	Historic environment record designation	Re-opening
Våmb quarry, Cementa, Skövde	Sweden	Permitting in and adjacent to protected areas	Operation

REFERENCES

N2K Group EEIG & Institute for European Environmental Policy (IEEP) 2019. Non-energy mineral extraction in relation to Natura 2000 – Case Studies. European Commission. Available at: https://ec.europa.eu/environment/nature/natura2000/management/docs/NEEI%20case%20studies%20-%20Final%20booklet.pdf

THE HE ENICON AND EXCEED PROJECTS. OBJECTIVES AND AMBITION TOWARDS CLIMATE NEUTRALITY

by

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OVERVIEW

The transition to a climate-neutral society by 2050 is both a critical challenge and an opportunity to build a better future for all. This objective is at the heart of the European Green Deal and in line with the EU's commitment to global climate action under the Paris Agreement. According to the International Energy Agency (IEA) the demand for nickel (Ni), cobalt (Co) and lithium (Li), will increase 21, 19 and 42 times respectively, within the next 20 years (IEA 2021).

If no action is taken, Europe will almost certainly see demand outstripping supply. What makes matters much worse is that the Ni/Co mining/processing/refining value chains are concentrated in the Democratic Republic of Congo (Co mining), Indonesia (Ni mining and refining based on High-Pressure Acid Leaching, HPAL), and China, whose role is rapidly growing. Also, Europe has a minor role in the rapidly expanding global Li value chain for mining and refining and is 100% reliant on its import (EU 2020).

ENICON and EXCEED HE projects aim to increase the involvement of Europe in the global value chains for energy transition metals. Both projects also participate in the Cluster Hub "Production of raw materials for batteries from European resources", a knowledge exchange platform facilitating collaboration among research institutes, industry and innovation stakeholders towards the production of raw materials for battery applications from primary and secondary resources available in Europe and the recycling of batteries, https://www.materialsforbatterieshub.eu/.

ENICON HE PROJECT, https://enicon-horizon.eu/

Europe faces a major challenge to ensure reliable, affordable and sustainable supplies of Ni and Co (i.e., Class-I Ni: > 99.8 wt% Ni, synthesised into battery-grade $NiSO_4$, and battery-grade Co, $CoSO_4$). The global state-of-the-art Ni/Co processing involves production of nickel from sulphidic Ni/Co ores and lateritic (oxidic) ores, while cobalt is a by-product of copper or nickel mining. Pyrometallurgy is the main technology used for treating high-grade sulphide concentrates (e.g., 7–11 wt% Ni). The Ni/Co concentrate is converted to a Ni/Co-rich sulphide matte (~70 wt% Ni) that is subjected to hydrometallurgical treatment with solvent extraction and electrowinning to produce battery-grade Ni and Co. Compared to its laterite competitors, the carbon footprint for this route is low (i.e., < 10 kg CO_2 per kg Ni). The drawbacks are large Co and Ni losses during flotation and converting/smelting, and the generation of a Ni/Co-containing slag. These drawbacks are tackled efficiently in ENICON.

Compared to Ni/Co-sulphidic ores, Ni/Co-lateritic ores are lower grade and mineralogically complex. In Europe, laterites are processed with a pyro-flowsheet, by ENICON partners Larco and Euronickel, into a FeNi (Class-II Ni) product (for the stainless-steel industry). Apart from having a large carbon footprint (Bartzas & Komnitsas 2015), the drawback of this process is its inability to produce battery-grade Ni (Class-I Ni). Also, this process generates slag that it may be disposed of in landfills and fails to valorise the Co that largely ends up in the FeNi (it contains 0.6–1.0 wt% Co). In the near future, as sulphide reserves are becoming depleted, increased focus will be on the processing of laterites (Harris 2019).

In contrast, Indonesia, the global Ni powerhouse, uses the HPAL process for laterite ores, that involves high pressures (e.g. 44 bar) and temperature (> 250 °C) during the H_2SO_4 leaching and consumes chemicals to regulate the pH and precipitate the so-called Mixed Hydroxide Precipitate (MHP), that is then re-dissolved in acid in the downstream hydro-processing to produce the battery-grade Ni (and Co). The process also generates solid waste streams (gypsum, Na_2SO_4), while the carbon footprint is twice that of the sulphide route. HPAL is not a sustainable process for the 21st century.

ENICON goes beyond the industrial state of the art and targets a double-sided "realistic innovation" approach (Fig. 1), while at the same time making scientific advances in Ni/Co mining, metal recovery, ultra-refining and mineral matrix valorisation. ENICON involves integrated geometallurgy–LCA–TEA and predictive thermodynamic modelling, enhances existing unit processes and adds complementary unit processes, in order to:

- improve Ni/Co yield and reduce the carbon footprint of existing sulphide and laterite routes;
- unlock Ni/Co potential of pyrite and silicate tailings using Boliden's bioleaching process, addressing also the issue of Ni-losses in silicate-based tailings;
- valorise slags from laterite pyro-route (Larco, Euronickel) and the sulphide pyro-route (Boliden); upgrade the FeNi product from EU-laterite processing to Class-I nickel, while recovering the Co present in the FeNi.

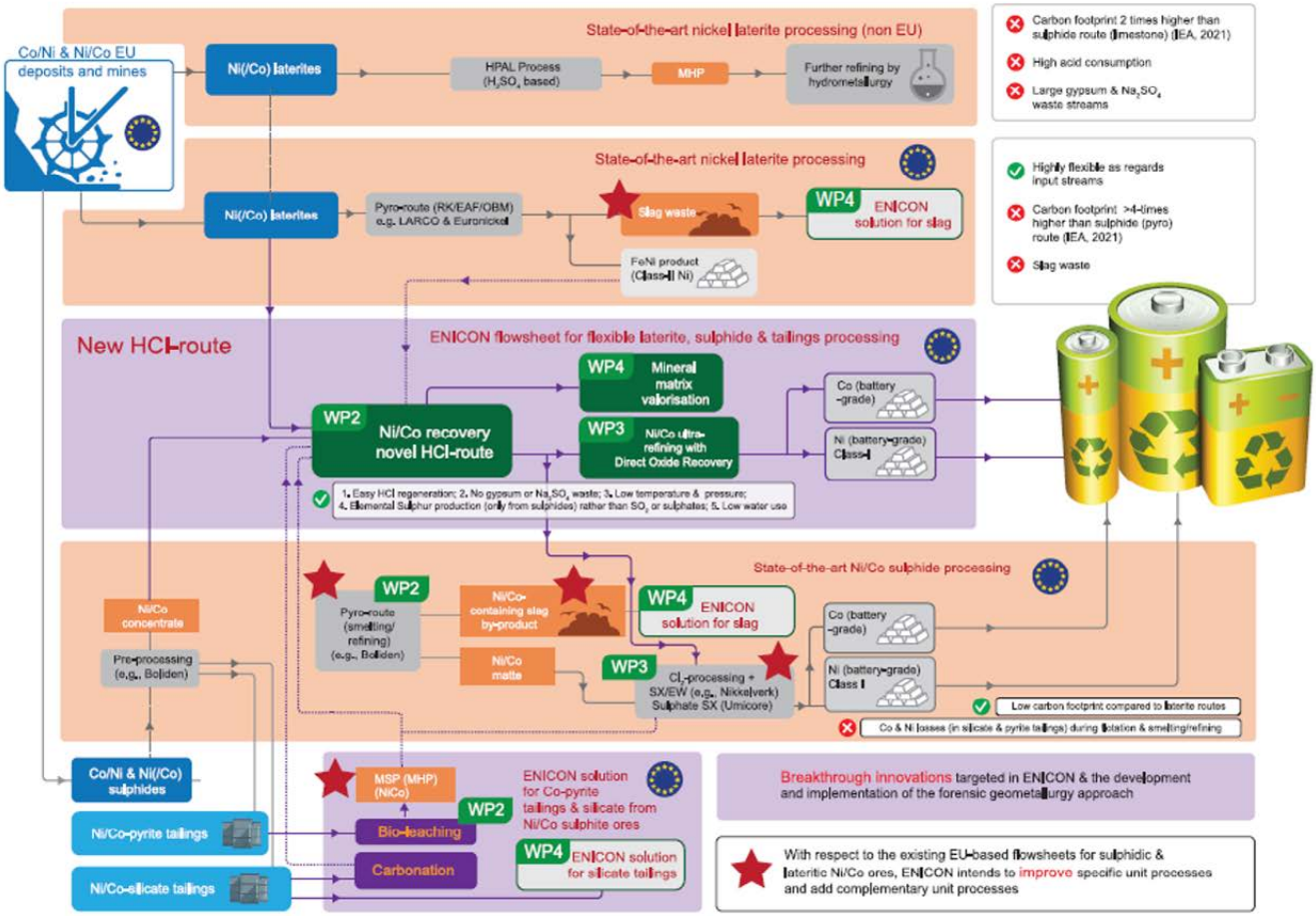

Fig. 1. How ENICON goes beyond the start of the art for Ni/Co mining, recovery and refining.

In parallel, ENICON develops a new, low-pressure, low-temperature, comprehensive hydrometallurgical process flowsheet for sulphide concentrates and laterite ores, which can also be adapted / extended for the MSP and MHP generated from the bioleaching of Ni / Co pyrite tailings, carbonated Ni-silicate tailings and FeNi from pyro-processing of laterites. The ENICON HCl-route reflects a "circular hydrometallurgy" perspective, is industry-appropriate and does not use expensive solvents; instead, it employs excess HCl, which is recovered, REACH-compliant and easily-accessed extractants such as TEHA, TBP and Cyanex 301.

EXCEED HE PROJECT, https://exceed-horizon.eu/

There are two primary sources of Li: brine deposits (salars), in which the Li grade is ~0.1 wt% Li_2O; and hard-rock deposits, with higher Li grade, 0.6–1 wt% Li_2O. Li mining is concentrated in just four countries: Australia (hard-rock mining, cf. Greenbushes), Chile & Argentina (cf. salar de Atacama) and China (cf. salars in Qinghai-Tibet plateau). Of even greater concern, the downstream processing and refining of battery-grade Li salts (e.g., $LiOH{\cdot}H_2O$, Li_2CO_3) is dominated by just one country, i.e., China (Tadesse et al. 2019). Thus, as Maroš Šefčovič, Vice-President of the EC, mentioned in his keynote speech at the Raw Materials for Europe Conference in Prague, Sep. 12, 2022 "The EU currently supplies only 1% of its own needs for key battery raw materials, such as lithium, cobalt and nickel. With raw materials becoming the world's most sought-after commodities due to

their fundamental role across our economies and societies, we must throw all our weight into secure and sustainable access of raw material".

Even though 27 hard-rock deposits have been identified in Europe – representing a resource potential of 8.8–21.7 Mt Li_2O – Europe has no major Li mining or refining (Gourcerol et al. 2019). It is true that EXCEED partner Keliber expects to commission a Li plant in Finland in 2024. But this single operation, which received a mining permit from the Finnish Safety and Chemical Agency (TUKES) on March 24, 2022, will not be enough to ease Mr Šefčovič's worries.

The EC and key actors in the European Battery Alliance have all emphasised that the primary mining of Li must begin in Europe. But apart from the Nordic countries there is little public interest for mining. Lithium projects in Portugal face strong opposition from several stakeholder groups. End of May 2023 it was announced that the Portuguese authorities approved the environmental impact assessment (EIA) for the Mina do Barroso spodumene mine project, owned by Savannah Resources and located in a world heritage site for agriculture. Portugal is Europe's biggest Li producer, which is used almost exclusively in the ceramics industry. The decision of the Serbian government in January 2022 to block the Rio Tinto Li-mining project in Jadar, was also the result of public opposition. Opponents of Li mining stress the need for more Li-recycling capacity in Europe, so that primary mining is avoided. However, the reality is that by 2040, recycled quantities of Cu, Li, Ni and Co from spent batteries could reduce their primary supply requirements by only ~10%, thus most European Li needs will be covered from primary resources, i.e., salars and hard-rock deposits. In Europe, which has nothing like the salars of Chile or Argentina, this will mean hard-rock deposits, supplemented by geothermal brines (of which there are limited reserves) and secondary Li-bearing resources.

EXCEED aims to move from single-metal Li mining to zero-waste, multi-metal/mineral mining. This needs to be coupled with sustainable mineral processing, leading to a suite of critical metals and minerals derived from sustainable metallurgical extraction and refining processes. As visualised in the Graphical Abstract (Fig. 2), EXCEED will recover CRMs (Nd/Pr, Nb, Ta, W, Be) and industrial minerals (quartz, feldspar, micas) as by-products from Europe's foremost Li hard-rock projects. EXCEED's case studies are two spodumene-bearing lithium-caesium-tantalum

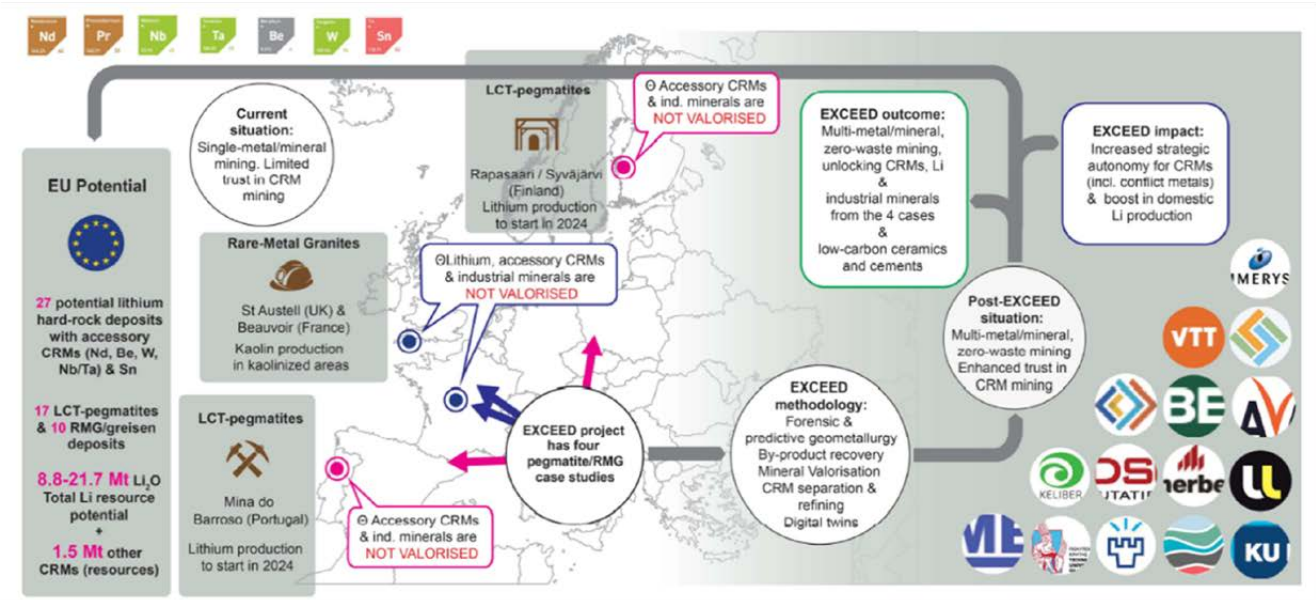

Fig. 2. EXCEED's graphical abstract.

(LCT) pegmatite deposits (Keliber's Rapasaari & Syväjärvi mines in Finland; Savannah's Mina do Barroso, Portugal) and two Rare-Metal Granite (RMG) deposits (Imerys' St Austell (UK) and Beauvoir (France) mines).

EXCEED's multimetal/mineral, zero-waste mining-and-refining approach adopts a mineral-centric, integrated methodology via the application of a first-of-its-kind predictive and forensic geometallurgy, supported by enhanced in-line characterisation tools and the development of digital twins. Using four premier European pegmatite and RMG case studies, EXCEED develops, upscales & demonstrates cost-effective, sustainable and responsible extraction routes for recovering the CRMs and industrial minerals as by-products from Li-bearing hard-rock ores. A suite of CRMs will be extracted and refined, while diverse industrial minerals will be refined and valorised in low-carbon building materials (Fig. 3). The EXCEED solutions can be replicated for many other European LCT-pegmatite and RMG deposits.

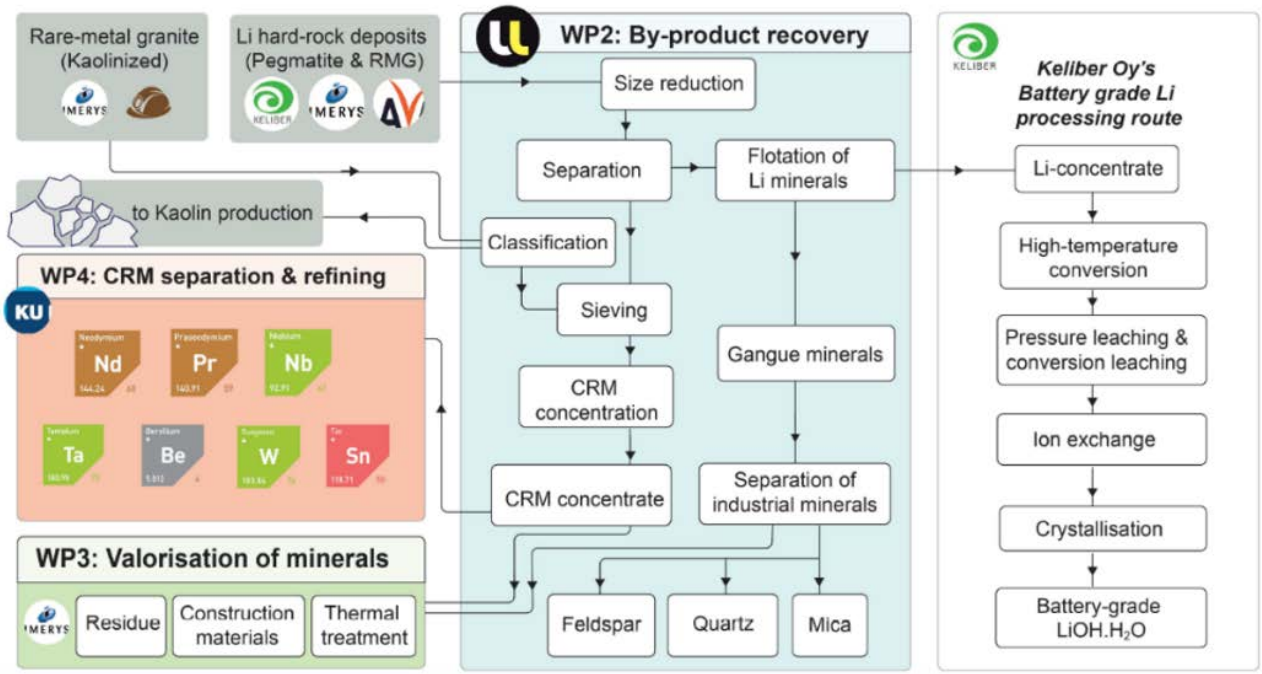

Fig. 3. EXCEED concept: recovery & refining of by-product CRMs (and other metals) along with industrial minerals separation and valorisation starting tom Li-bearing pegmatite and Rare-Metal Granite deposits/mines.

ACKNOWLEDGEMENTS

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REFERENCES

Bartzas, G. & Komnitsas, K. 2015. Life cycle assessment of ferronickel production in Greece. Resources, Conservation and Recycling 105, 113–122. Available at: https://doi.org/10.1016/j.resconrec.2015.10.016

European Union (EU) 2020. Critical Raw Materials Resilience: Charting a Path towards greater Security and Sustainability. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0474

Gourcerol, B., Gloaguen, E., Melleton, J., Tuduri, J. & Galiegue, X. 2019. Re-assessing the European lithium resource potential – A review of hard-rock resources and metallogeny. Ore Geology Reviews, 109, 494–519. Available at: https://doi.org/10.1016/j.oregeorev.2019.04.015

Harris, B. 2019. The future of Ni-Co-Cu processing in the age of lithium-ion batteries, ALTA 2019 Nickel/Cobalt/Copper Conference, 20–22 May 2019, Perth, Western Australia.

IEA (International Energy Agency) 2021. The Role of Critical Minerals in Clean Energy Transitions. Available at: https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

Tadesse, B., Makuei, F., Albijanic, B. & Dyer, L. 2019. The beneficiation of lithium minerals from hard rock ores: A review. Minerals Engineering 131, 170–184. Available at: https://doi.org/10.1016/j.mineng.2018.11.023

PRELIMINARY ASSESSMENT OF THE SOCIAL LICENSE TO OPERATE IN FOUR EUROPEAN LITHIUM PROJECTS

by

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Lithium is needed for green energy transition, and it is produced outside of European Union (EU). However, EU has promising lithium projects, but such as regarding mining and mineral exploration in general, their local acceptance may be important for their viability (Komnitsas 2020, Graham et al. 2021). Europe has a record of mining-related disputes (Kivinen et al. 2020, Lesser 2021), and the recent obstruction of the Jadar Valley lithium project in Serbia by the government (see De Layne et al. 2022) is an example of the importance of the social license to operate (SLO) also for the green energy transition. SLO means acceptance or approval of a project by the local community or society (Thomson & Boutilier 2011).

Four European lithium projects are preliminary assessed regarding their acceptance and possible disputes: Rapasaari and Syväjärvi in Kaustinen (referred hereby as Kaustinen) in Finland, St. Austell in Great Britain, Beauvoir in France, and Mina do Barroso in Portugal (Fig. 1). For this purpose, a literature and online media report search and review were carried out. Search was carried out by a simple Google query using company and project names as keywords. This procedure based on protest event analysis (PEA; Koopmans & Rucht 1999) is an appropriate first and remote approach to detect any local disagreements regarding the projects. According to Earl et al. (2004), opposition needs media attention for its protest and demands and online media reports are available and useful for that purpose. In addition, corporate websites of the companies in question were also checked to see which community relationship strategies they communicate online, following the methodology described by Eerola (2021). The projects are case studies of the Horizon Europe Project EXCEED ("Cost-effective, sustainable and responsible extraction routes or recovering distinct critical metals and industrial minerals as by-products from key European hard-rock lithium projects", Grant Agreements no. 101091543). The mentioned projects aim for lithium production from pegmatites/granites/kaolin.

The Rapasaari and Syväjärvi projects owned by Siboney Stillwater Keliber Oy are in Kaustinen, western Finland (Figs. 1 and 2). The company aims to start production from pegmatites in 2024. Beyond Rapasaari and Syväjärvi, there are also prospects of Länttä, Outojärvi, and Emmes. The region has no mining-related

disputes, but the mine sites are close to Natura 2000 area (Fig. 2). Eerola (2021) shown that the Keliber was one of the twenty companies operating in Finland that communicated online about its SLO-related strategies.

Fig. 1. Location of the four case studies.

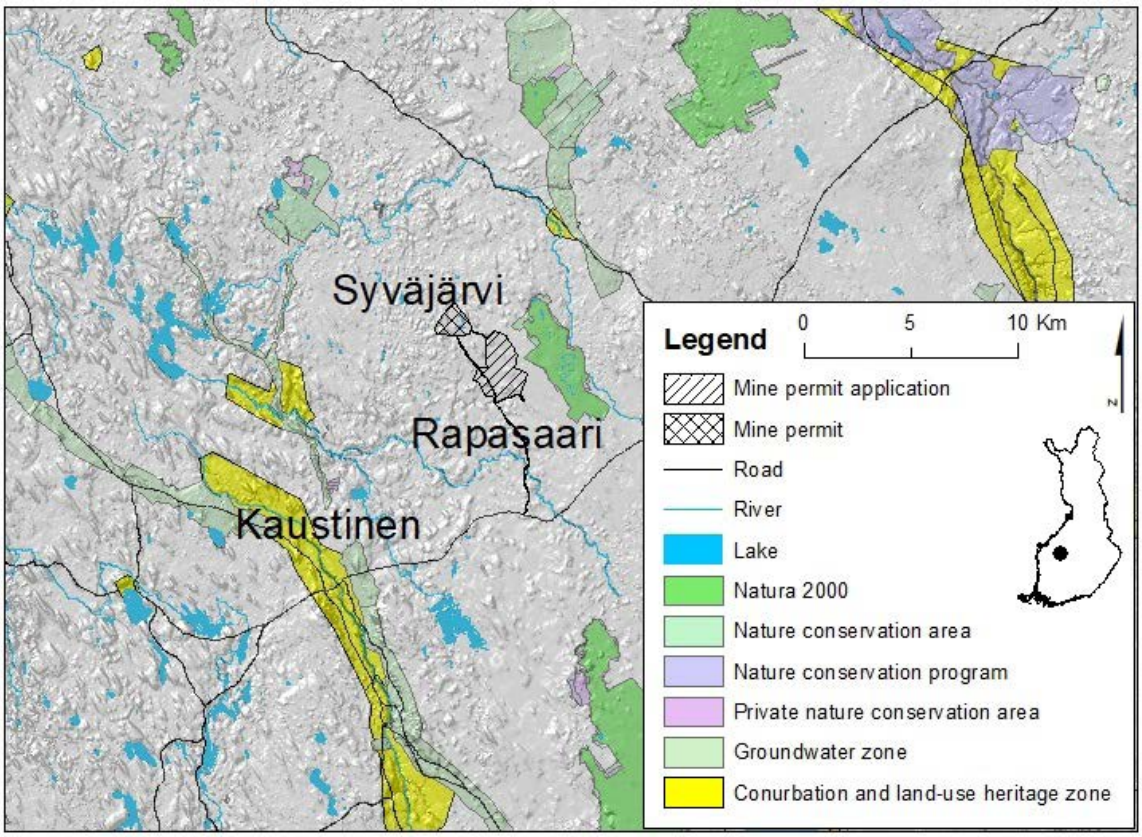

Fig. 2. The Kaustinen lithium project in western Finland.

The Mina do Barroso project is owned by Savannah Resources in northern Portugal. Production would be from LCT-pegmatite ores. At the end of May 2023, the Portuguese authorities approved the environmental impact assessment (EIA) for the Mina do Barroso spodumene mine project (Silva 2023).

The Trevalour project in St. Austell, Cornwall, UK, is operated by Cornish Lithium plc. It is in an old mining heritage area and the project is in exploration stage. The company aims to produce lithium from granite/kaolin and thermal water.

The Emili project in Beauvoir (Allier), western France is owned by Imerys Minerals Ltd. It is planned to start production from granite in 2028.

Based on the corporate websites, all companies practice active stakeholder engagement and communication to maintain a good company-community relationship. Keliber's project was not among the twenty cases of mining-related disputes mapped in Finland by Eerola (2022), but environmental concerns regarding the Kaustinen project have been expressed by local non-governmental organisations and landowner and fishery associations (Vihanta 2019). They appealed against the permit approval, but it was in great part rejected by the Supreme Court ruling (Holopainen 2021). Except of the Mina do Barroso, there seems to not have any open resistance towards the projects and quite positive picture with industry views is given for all other projects in the media. Beyond other mining-related disputes in Portugal (see Domingues 2022), Mina do Barroso is also the only project with critical academic articles on it (e.g., Chaves et al. 2022, Dunlap & Riquito 2023).

Further steps would be to study the associated land use and the sites in more detail regarding the project location in potentially sensitive contexts.

REFERENCES

Chaves, C., Pereira, E., Ferreira, P. & Guerner Dia, A. 2022. Concerns about lithium extraction: A review and application for Portugal. The Extractive Industries and Society 8, 100928. Available at: https://doi.org/10.1016/j.exis.2021.100928

De Layne, G. 2022. Serbia revokes Rio Tinto lithium mine permits following protests. BBC News, 21 January 2022. Available at: https://www.bbc.com/news/world-europe-60081853

Domingues, N. 2022. Lithium prospection in Portugal for E-mobility and solar PV expansion. Commodity 1, 98–114. Available at: https://doi.org/10.3390/commodities1020007

Dunlap, A. & Riquito, M. 2023. Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal, Energy Research & Social Science 95, 102912. Available at: https://doi.org/10.1016/j.erss.2022.102912

Earl, J., Martin, A., McCarthy, J. D. & Soule, S. 2004. The use of newspaper data in the study of collective action. Annual Review of Sociology 30, 65–80. Available at: https://doi.org/10.1146/annurev.soc.30.012703.110603

Eerola, T. 2021. New low-impact mineral exploration technologies and the social license to *explore*: Insights from corporate websites in Finland, Cleaner Environmental Systems 3, 100059. Available at: https://doi.org/10.1016/j.cesys.2021.100059

Eerola, T. 2022. Corporate conduct, commodity, and place. Ongoing mining and mineral exploration disputes in Finland and their implications for the social license to operate. Resources Policy 76, 102568. Available at: https://doi.org/10.1016/j.resourpol.2022.102568

Graham, D. G., Rupp, J. A. & Brungard, E. 2021. Lithium in the Green Energy Transition: The quest for both sustainability and security. Sustainability 13, 11274. Available at: https://doi.org/10.3390/su132011274

Holopainen, H. 2021. The lithium mining company Keliber can start to prepare opening of a mine – appeals on environmental permit were rejected in great part. Yle Uutiset, 18.6.2021. (in Finnish). Available at: https://yle.fi/a/3-11988940

Kivinen, S., Kotilainen, J. & Kumpula, T. 2020. Mining conflicts in the European Union: environmental and political perspectives. Fennia, 198, 163–179. Available at: https://doi.org/10.11143/fennia.87223

Komnitsas, K. 2020. Social license to operate in mining: Present views and future trends. Resources, 9, 79. Available at: https://doi.org/10.3390/resources9060079

Koopmans, R. & Rucht, D. 1999. Protest event analysis. Mobilizations, 4, 231–259. Available at: https://doi. org/10.1093/acprof:oso/9780198719571.003.0014

Lesser, P. 2021. SLO good practices and recent disputes. Illustrative examples across Europe. Mining and Metallurgical Regions of Europe (MIREU) Project, Brussels, 17–42. Available at: https://mireu.eu/sites/default/files/2021-06/Illustrative%20Examples%20Report.pdf

Silva, B. 2023. Savannah gets "green light" to build up the Barroso lithium mine conditioned by environmental agency of Portugal. Negócios 31.5.2023. (in Portuguese). Available at: https://www.jornaldenegocios.pt/empresas/energia/detalhe/savannah-tem-luz-verde-condicionada-da-apa-para-constuir-mina-de-litio-do-barroso

Thomson, I. & Boutilier, R. G. 2011. The social license to operate. In: Darling, P. (ed.) SME Mining and Engineering Handbook. Littleton, Co., 1779-1796.

Vihanta, S. 2019. Fears about eutrophication of the Perho River – fishery, nature conservation and landowner associations appealed on Keliber's environmental permit. Yle Uutiset, 2.7.2019. (in Finnish). Available at: https://yle.fi/a/3-10709728

INNOVATION AND CO-OPERATION LEADING TO INCREASED SELF-SUFFICIENCY, CIRCULARITY, AND SUSTAINABILITY IN RAW MATERIALS

by

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The Finnish government has set the ambitious goal of Finland being a carbon-neutral and successful circular economy in 2035. The target is a national response to European Green Deal (European Commission 2019) which is Union's response to fight climate change and environmental degradation. The European Green Deal targets for zero net emissions of greenhouse gases and economic growth decoupled from resource use by 2050. More sustainable and circular critical raw materials economy is also one pillar in the recent European Critical Raw Materials Act which aims to increase EU self-sufficiency in critical raw materials (European Commission 2023).

Achieving the goal requires efficient use of natural resources within the economy, and the following national targets for circular economy have been set to speed up the process (Ministry of Environment 2021):

- The consumption of non-renewable natural resources in the Finnish economy will decrease, and the sustainable use of renewable natural resources increases so that the total domestic consumption of primary raw materials does not exceed the level of 2015 in 2035. The natural resources used to manufacture export products are not covered by the target.
- Resource productivity will double from the situation in 2015 by 2035.
- The circularity rate of materials will double by 2035.

In practise, the increased circularity of industries and communities is driven by a national Circular Economy Green Deal, which is currently under specification (Ministry of Environment 2023). The national Green Deal includes a common framework and criteria, and commitments to promote a low-carbon circular economy by the parties that wish to participate. Work is divided into two intermingled processes:

1. **Scientific scenario work (MaViSkene project).** Aim is to create status quo and scenarios of natural resources use, environmental effects, and monetary flows within the economy of Finland, and create understanding of circular economy opportunities for industries and communities to support their commitments.

2. **Groundwork and ground rules for the Circular Economy Green Deal.** Ministry of the Environment, in co-operation with Ministry of Economic Affairs and Employment, coordinates discussions between researchers and a stakeholder network that include companies, municipalities, and other actors from all economic sectors in Finland.

Within this entity we, at the Geological Survey of Finland (GTK), are involved in creating capabilities for monitoring the goals of the circular economy program and strengthening the knowledge base for circular economy commitments of various actors to support their decisions. The two-year (2022–2023) project MaViSkene is led by the Finnish Environment Institute (SYKE) and, in addition to GTK, the Technical Research Centre of Finland (VTT), Natural Resources Institute (Luke) and Statistics Finland are involved in the implementation. At GTK, our responsibility is to examine the extractive industries in Finland and it´s circular economy opportunities. This includes examination of circular economy agreements, goals, and actions in the extractive industry that affect future material flows; updating of the database of material flows of the existing mining sector for scenario work (mining model); creation of a material-flow scenario for the extractive sector for the year 2035 in Finland in cooperation with SYKE, and producing information about national circular economy measures for the use of extractive industry.

During the process, we have created a status quo of the current material flows within the mining sector based on site-specific data. In addition, we have examined circular economy measures in the mining industry now, and their implementation possibilities in the future. We have had three circular economy stakeholder workshops with mining industry representatives held in co-operation with Ministry of the Environment, VTT and SYKE. As an outcome, we have formulated a circular economy framework for the mining sector in Finland (Fig. 1) and identified the most promising developments for 2035. The work will continue with scenario modeling supporting the Green Deal commitments.

Our analysis shows that mining companies already widely apply practises that advance circular economy targets. One reason is economics, as handling of large amounts of materials is costly. Many companies also actively aim towards new products from their side streams and waste streams and have adopted "a wasteless mine" thinking. In addition, there is active research ongoing for innovative

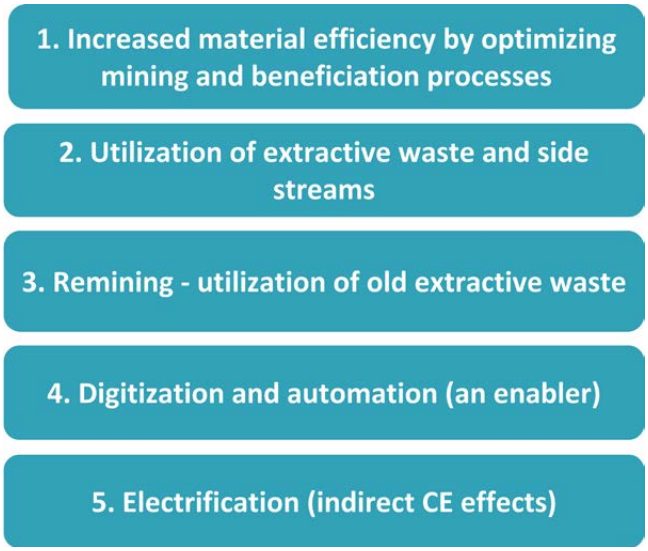

Fig. 1. Circular economy framework for mining industry.

uses of tailings in mine fillings and as alkali activated concrete-like materials for increased material and cost efficiency and environmental protection (e.g., Kiventerä et al. 2020, Solismaa et al. 2021). In general, internal rotation of materials within a mining area is an important action for material efficiency in mines. As each mine has its own type of material to utilise, also the solutions are mine-specific. There are several actions to be considered, that would increase circularity and can create value for the mining companies. Examples include use as aggregates outside the mining area, mine filling, and infrastructure inside the mining areas, use of tailings as a raw material for concrete, and providing fully new products from the side streams. As many ores in Finland are complex, there are also possibilities for increased production of additional critical raw materials from the ores by optimising the beneficiation processes.

In our analysis, we also identified the most important bottlenecks for increased circularity in the minerals sector in Finland. These are **1)** inefficient information flow of available raw materials for potential users, **2)** transportation costs of low-value products, **3)** tight conditions for the waste status in environmental regulations, **4)** insufficient information management and circular economy know-how, and **5)** the lack of circular economy ecosystems.

What comes to national material flow statistics in Finland, there is no single action identified that would significantly reduce mineral waste from mines by 2035. On the contrary, the material flow is expected to increase due to the increase in worldwide demand and with new mining projects. However, in new mining projects there are more possibilities to plan the mine and the process from the beginning to advance circularity and climate neutrality. In this target, the circular economy targeting mind set of company leadership has a great importance.

The European Union is facing a great challenge in improving self-sufficiency in raw materials without compromising environmental, social, or economic sustainability. In this task, we need both increased primary production and increased efficiency in existing mines but, most of all, innovative thinking. Circular economy focused design of mining sites and unprejudiced co-operation between different actors are in the focal point of this development.

REFERENCES

European Commission 2019. The European Green Deal. Communication from the commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions. Brussels, 11.12.2019 COM(2019) 640 final. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

European Commission 2023. Proposal for a regulation of the European Parliament and of the Council establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52023PC0160

Kiventerä, J., Perumal, P., Yliniemi, J. & Illikainen, M. 2020. Mine tailings as a raw material in alkali activation: A review. International Journal of Minerals, Metallurgy and Materials 27, 8, p.1009. Available at: https://doi.org/10.1007/s12613-020-2129-6

Ministry of Environment 2021. Government resolution on the strategic programme for Circular Economy. Ministry of the Environment. Resolution 8 April 2021. Available at: https://ym.fi/en/strategic-programme-to-promote-a-circular-economy

Ministry of Environment 2023. Circular Economy Green Deal. Available at: https://ym.fi/en/circular-economy-green-deal. [Accessed 29.8.2023]

Solismaa, S., Torppa, A., Kuva, J., Heikkilä, P., Hyvönen, S., Juntunen, P., Benzaazoua, M. & Kauppila, T. 2020. Substitution of Cement with Granulated Blast Furnace Slag in Cemented Paste Backfill: Evaluation of Technical and Chemical Properties. Minerals 11(10), 1068. Available at: https://doi.org/10.3390/min11101068

MACHINE LEARNING TOPIC DETECTION OF SOCIAL MEDIA ATTITUDES ABOUT MINERAL DEVELOPMENT IN EUROPE

by

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INTRODUCTION

The green transition requires a huge amount of mineral resources to build the infrastructure and technology that produces, stores, and transmits low-carbon energy (U.S. Department of Energy 2010). These minerals include 'critical minerals', which are definitionally at a high risk of supply chain disruption. The worldwide COVID-19 pandemic highlighted many of the vulnerabilities inherent in the international supply of goods and materials, including critical minerals (Giese 2022, Zhu et al. 2020). This has also been exacerbated in Europe by the Russian invasion of Ukraine, which has caused many challenges for European energy production and distribution. Because of these vulnerabilities, it is becoming increasingly important to produce minerals as locally as possible (Kuzemko et al. 2022). At the same time, many developed economies have diversified away from primary resource production, and the idea of local mining in many member countries of the EU has become anachronistic to people who have not lived near active mining operations for many years. This has led to tension between some European developers of critical minerals and their host communities in Europe and elsewhere (Dunlap & Riquito 2023, Eerola 2022, Lesser et al. 2021, Ocelík et al. 2021).

Social license is a measure of the social acceptability of a given industry, organisation, or project (Thomson & Boutilier 2011). Lack of a social license in mining projects is a major risk to expensive and necessary mineral development operations across the world (Davis & Franks 2014). Measuring and understanding the social license of the mining industry can be slow, and because the social license is a dynamic and evolving phenomenon, measurements of the social license can often lag behind the real-time sentiment and concerns of stakeholders. That is why attention has been paid in recent years to developments in natural language processing as a means of discovering and analysing issues and narratives in real time, in order to identify and ameliorate concerns before they become problems before they become insurmountable obstacles to necessary sustainable development efforts (Boutilier & Bahr 2020). In this presentation, we discuss the use of natural language machine-learning methodologies for understanding the social license of critical mineral development in the EU.

METHODOLOGY

The SEMACRET project consists of several working packages related to geological, geophysical, and geochemical exploration at reference sites in four EU countries: The Czech Republic, Finland, Poland, and Portugal. As a part of that exploration, it is important to understand public sentiment around mining in those reference countries. In order to dynamically assess public sentiment and issues in these areas, we are searching social media for relevant texts in the four reference languages, which serve as the dataset for natural language analysis. So far, we have used an academic license to search Twitter for words related to mining in each of the languages from 2006 to early 2023, and Table 1 shows the preliminary search terms and the number of texts they produced.

Table 1. First-pass search terms by language.

Language	Native Speakers (Millions)	Target Population (Millions)	Search Terms ('mining')	Tweets
Finnish	5.8	5.5	'kaivostoimintaa'	1775
Portuguese	232	10.3	'mineração' AND 'portugal'	209
Polish	40	37.8	'górnictwo'	59611
Czech	10.7	10.5	'hornictví'	624

For the most part, the number of tweets are reasonably proportionate to the size of the traget population. One immediate difficulty shown in Table 1 is that Portuguese has a much higher native speaking population than that of Portugal itself. For this reason, the generic mining term "mineração" was combined with "portugal" in the initial search, in the hopes of producing only texts about mining within the reference country. This led to a disproportionately small number of tweets in Portuguese, which will be re-examined as this work progresses.

Once the data of interest were collected, we used a computational natural language processing method called Latent Dirichlet Allocation (LDA) to identify the topics that were most frequently discussed by people speaking about mining. As a statistical metholodogy, LDA assesses the probability that a given text is about a given topic based on the liklihood of certain words being used in that text (Blei et al. 2003, Steyvers & Griffiths 2007). The algorithm we used is mostly language agnostic, particularly for European writing systems that use the same latin alphabet and employ similar grammatical features, e.g. discrete written words that are set apart from each other by a space (Chew & Chew 2019, Kamyab 2019). This means that we were able to use the same algorithm for processing all languages, with only minor modifications to the input files.

The LDA method produces "bags of words", which signify a group of words that are most likely to appear together when discussing a given topic. This requires some interpretation, in order to understand what the topic actually represents. For example, a bag that consists of the words "production", "coal", "price", "market", "cost", "electricity", "increase", "ton", and "demand" can be reasonably be interpreted to be talking about coal production. For bags of words that are more ambiguous, the LDA model gives us other contextual clues for interpreting the topics, such as the texts that contributed the most to the determination of the topic in the model, the texts that most represent the topic, and the identity of the speakers who most mentioned the topic.

The topics generated by this methodology across all four languages are shown in Table 2, which shows that the 20 topics identified in this case can be further broken into four groups. It is not surprising that the polish language data should produce its own set of distinct topics, since there were orders of magnitude more Polish texts than texts in the other languages. Polish writers also discussed many of the other topics mentioned, but the topics in the "Polish Topics" category were unique and specific to Polish writers.

Table 2. Groups of Identified Topics.

Polish Topics	Legal Topics	Social Topics	Development Topics
Polska Grupa Energetyczna	Corporate Corruption	COVID in Mines	Exploration
Polish Politics	Mining Agreements	Mine Workers	Space Mining
Polish Resource Nationalism	Mining Subsidies	Unrest	Green Transition Minerals
Coal Sourcing	Mining Law	Economic Knock-on	Natural Gas
Coal Production	Regional Mining Bans	Mining History	
Climate Ministry			

After the topics have been identified, it is possible to cross-search texts for mentions of all topics, in order to determine which topics are most frequently mentioned together. This helps us to understand the larger narratives around the topics that are being created by social media users, and how individual topics are related to each other. This allows us to produce an adjacency matrix of how often each topic is mentioned with each other topic, which in turn allows us to produce and quantitatively analyse a co-mention network graph. Figure 1 shows the topic co-mention network, in which the colours of the nodes correspond to the groups in Table 2, and their vertical position within the network corresponds to their eigenvector centrality, which is a measure of a node's importance in the overall network.

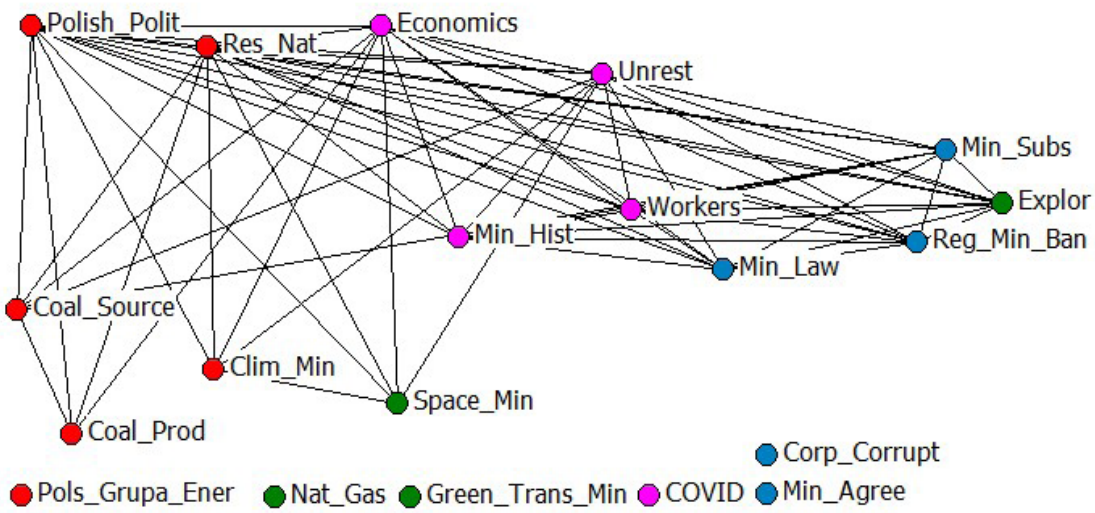

Fig. 1. Topic co-mention network graph.

Figure 1 shows that there is a cluster of several highly connected nodes at the top, most strongly represented by the Polish topics of internal politics and resource nationalism, which are also connected to economics and general social unrest. Coal sourcing and production are connected with politics, resource nationalism, and economics, and coal sourcing is also tied to social unrest and mining subsidies. The new (2020) climate ministry of Poland is also connected to the same issues, as well as the space mining topic. On the left side of Figure 1, there is a cluster of highly connected nodes related to legal issues around mining law, regional mining bans, and mining subsidies. These topics are all related to the Polish topics, but were also mentioned by tweets from the other regions as well.

NEXT STEPS

The next major tasks have to do with refining the search terms to 1) create a more proportional sample of texts from each target language and 2) better represent native understanding of the relevant mining concepts. In order to achieve the first task, the search terms will be expanded and more nuanced search criteria will be implemented. This task will also be helped by the second task, in which native speaking SEMACRET partner members will help to correct improper grammer and syntax in the search terms. It has been pointed out, for example that of the polish words to describe mining, "górnictwo", doesn't have the same functional meaning as the words in the other languages. Having native speakers to help with the data collection phase will help us to produce more relevant topic models and develop a better sense of the topics that cross cultural and linguistic boundaries.

In addition to the above next steps topic analysis and other quantitative linguistic methods will be applied to each language individually, so that the country specific issues can also be better identified and understood. These improvements will help to develop a real-time social media monitor that can help to study mining related issues as they emerge and evolve.

REFERENCES

Blei, D. M., Ng, A. Y. & Jordan, M. I. 2003. Latent Dirichlet allocation. Journal of Machine Learning Research 3(4–5), 993–1022. Available at: https://doi.org/10.1016/b978-0-12-411519-4.00006-9

Boutilier, R. G. & Bahr, K. 2020. A natural language processing approach to social license management. Sustainability (Switzerland) 12(20). Available at: https://doi.org/10.3390/su12208441

Chew, P. A. & Chew, J. A. G. 2019. Analyzing transnational narratives in Twitter: an unsupervised approach using PARAFAC.

Davis, R. & Franks, D. 2014. Costs of Company-Community Conflict in the Extractive Sector. Available at: http://www.hks.harvard.edu/m-rcbg/CSRI/research/Costs of Conflict_Davis Franks.pdf

Dunlap, A. & Riquito, M. 2023. Social warfare for lithium extraction? Open-pit lithium mining, counterinsurgency tactics and enforcing green extractivism in northern Portugal. Energy Research & Social Science 95, 102912. Available at: https://doi.org/10.1016/J.ERSS.2022.102912

Eerola, T. 2022. Corporate conduct, commodity and place: Ongoing mining and mineral exploration disputes in Finland and their implications for the social license to operate. Resources Policy 76(August 2021), 102568. Available at: https://doi.org/10.1016/j.resourpol.2022.102568

Giese, E. C. 2022. Strategic minerals: Global challenges post-COVID-19. The Extractive Industries and Society 12, 101113. Available at: https://doi.org/10.1016/J.EXIS.2022.101113

Kamyab, E. 2019. Multilingual Gaussian Latent Dirichlet Allocation. Master's Thesis, University of Gothenburg.

Kuzemko, C., Blondeel, M., Dupont, C. & Brisbois, M. C. 2022. Russia's war on Ukraine, European energy policy responses & implications for sustainable transformations. Energy Research & Social Science 93, 102842. Available at: https://doi.org/10.1016/J.ERSS.2022.102842

Lesser, P., Gugerell, K., Poelzer, G., Hitch, M. & Tost, M. 2021. European mining and the social license to operate. The Extractive Industries and Society 8(2), 100787. Available at: https://doi.org/10.1016/J.EXIS.2020.07.021

Ocelík, P., Lehotský, L. & Černoch, F. 2021. Beyond our backyard: Social networks, differential participation, and local opposition to coal mining in Europe. Energy Research & Social Science 72, 101862. Available at: https://doi.org/10.1016/J.ERSS.2020.101862

Steyvers, M. & Griffiths, T. L. 2007. Probabilistic topic models. In: Landauer, T., McNamara, S. D. & Kintsch, W. (eds) Latent Semantic Analysis: a Road to Meaning. Laurence Erlbaum. Available at: https://doi.org/10.1145/2133806.2133826

Thomson, I. & Boutilier, R. G. 2011. Social license to operate. In: Darling, P. (ed.) SME Mining Engineering Handbook Society for Mining, Metallurgy, and Exploration, INC. (3rd ed.), 1779–1796. Available at: https://doi.org/10.1007/s10551-015-2976-7

U.S. Department of Energy 2010. Critical Materials Strategy. Available at: https://doi.org/10.1007/s00126-014-0555-y

Zhu, G., Chou, M. C. & Tsai, C. W. 2020. Lessons Learned from the COVID-19 pandemic exposing the shortcomings of current supply chain operations: A long-term prescriptive offering. Sustainability (Switzerland) 12(14). Available at: https://doi.org/10.3390/SU12145858

CRM-GEOTHERMAL: RAW MATERIALS FROM GEOTHERMAL FLUIDS

by

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INTRODUCTION

The energy and digital transitions require a large amount of mineral raw materials, some of which are considered 'critical' by the European Union. These Critical Raw Materials (CRM) are predominantly imported from non-European countries where environmental and ethical standards may be less strict than in the EU. However, the EU has largely untapped resources at its disposal in geothermal fluids, some of which contain significant amounts of CRMs.

The EU-funded CRM-geothermal project therefore proposes to combine the extraction of mineral raw materials and geothermal heat, a renewable energy resource from the ground that is available 24 hours per day. The technology solution developed by CRM-geothermal will thus help Europe fulfil the strategic objectives of the EU Green Deal and the Agenda for Sustainable Development while reducing dependency on imported CRM.

The combined extraction of heat and minerals from geothermal reservoirs offers a series of advantages: maximising returns on investment; minimising environmental impact; avoiding additional land use; leaving no 'conventional' mining legacies; achieving near-zero carbon footprint; enabling domestic supplies of CRM.

CRM-geothermal is coordinated by the Helmholtz Zentrum Potsdam Deutsches Geoforschungszentrum (GFZ) based in Potsdam, Germany. The research consortium consists of 20 partners, involving 14 EU-based and 6 associated partners from UK, Switzerland and Kenya, covering academic and industry backgrounds.

PROJECT APPROACH

Although Critical Raw Materials are known to occur in geothermal fluids, there are still many uncertainties concerning their occurrence in different geological settings and the sustainability of their extraction. The actual extraction process is also a major challenge, requiring technology development. The Horizon Europe-funded CRM-geothermal project therefore aims to:

- establish an overview of the potential for raw materials in geothermal fluids for a large range of elements across the EU and third countries;
- determine the source of selected CRM, their mobility and potential for sustained extraction from geothermal brines;
- develop and optimise innovative extraction technologies for selected CRM from geothermal brines that can form a business case for European SMEs;
- assess the environmental-social-economic viability, create transparent and traceable value chains, and foster ethical sourcing of CRM;
- demonstrate at a pilot site the extraction technology for at least one CRM at the scale of a mini-plant and evaluate the system's sustainability.

The CRM-geothermal concept is illustrated in Figure 1.

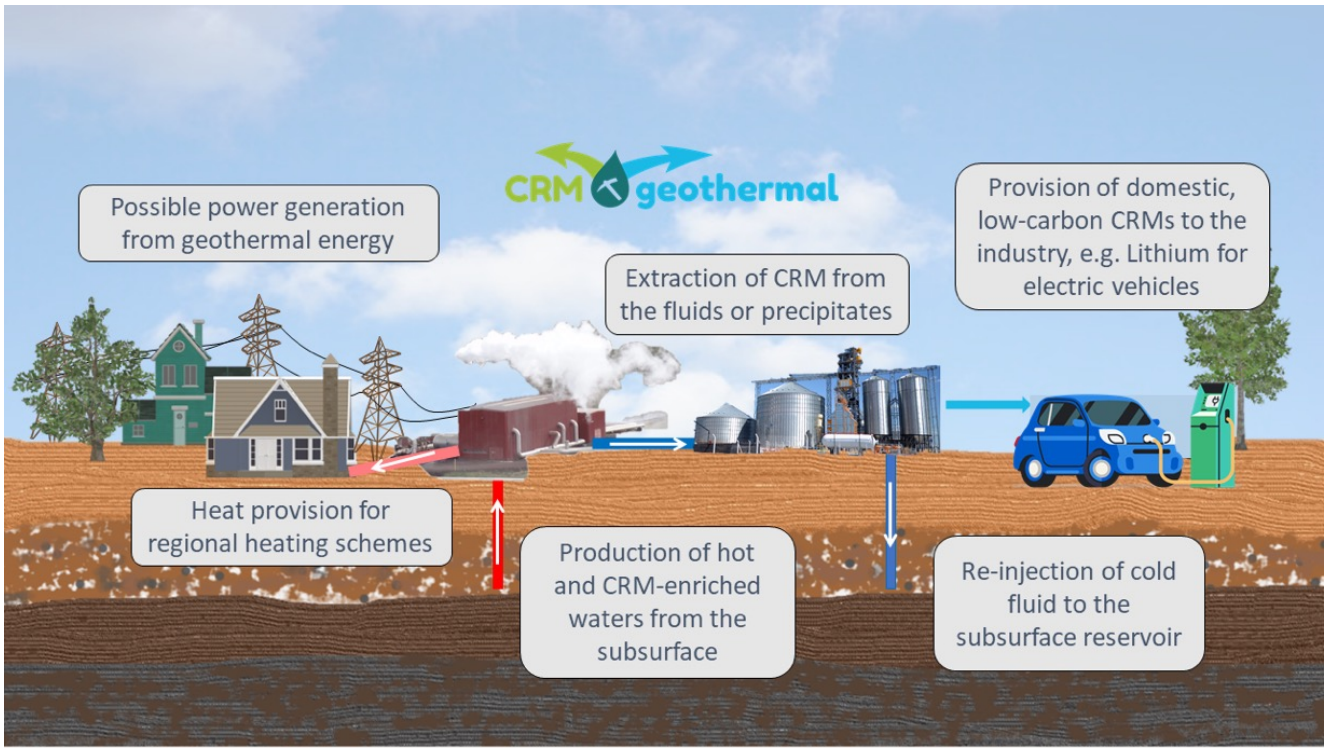

Fig. 1. CRM-geothermal concept.

PROJECT IMPLEMENTATION

The overall concept of the CRM-geothermal project is to use deep geothermal brines from geothermal plants as a resource and extract valuable components from the water and gas phases and associated precipitates. This challenge is approached from six different angles:

1. **Screening and mapping of CRM content in geothermal settings**
   To assess overall supply potential, CRM-geothermal builds a database with a view to assessing the CRM content in geothermal brines, gases and scales across Europe and the East African Rift countries by collecting and reviewing relevant publications and reports. New data are added from sampling various geothermal fluids. The data will be visualised in a CRM-geothermal fluid atlas. Data mining is applied to evaluate the data and highlight correlations between geothermal settings and CRM content.
2. **Geological controls of CRM mobility, source and long-term sustainability**
   Depending on the geological settings, different types of fluids with different elemental contents, including CRM, occur all over Europe. The geological formations used for geothermal energy production can be classified according to their fluid properties and their geological regions. CRM-geothermal evaluates the potential of different geological settings for combined extraction by (i) quantifying the long-term sustainability of extraction of CRM; (ii) investigating the enrichment processes of CRM in scales from high enthalpy settings; and (iii) quantifying REE + Y enrichment in alkaline geothermal areas.
3. **Development and optimisation of technologies and processes to extract CRM from geothermal fluids**
   For CRMs, which are known to occur in geothermal fluids in exploitable concentrations (such as Li, Sr, He), suitable extraction methods that do not interfere with the heat exchange process are needed. Extraction/separation techniques exist, but need to be adapted to the harsh conditions of such systems (high temperatures, pressures and salinities, i.e. competing ions). Combinations of materials and flow-schemes are assessed at lab-scale to optimise systems for different geothermal settings and CRM.
4. **Deployment of the combined extraction of CRM and energy from geothermal reservoirs**
   The technological developments will be accompanied by assessments of environmental and social impacts to ensure good governance. An UNFC/UNRMS-compliant reporting template will be developed to create trust among investors, regulators and the public. The project will advance key reference points for stakeholder engagement, in order to obtain and maintain a 'social license to operate'.
5. **Testing, validation, integration (of design requirements, systems and components)**
   The extraction materials and technologies will be tested at a pilot site in Cornwall, which is currently designed for production of Li-enriched brines (though production of low-grade heat is also being investigated. The field-scale Li-recovery testing will be undertaken using a 'miniplant', which includes all the process steps of the extraction in a modular, mobile plant. The pilot site will also be used to test the ESG impact assessment methods developed. Data from the experiments will inform tests of the economic models.

6. Market deployment

Combined extraction creates new business opportunities for both SMEs and larger companies, and its economics under likely future market developments will be investigated with a view to proposing suitable business models.

TESTWORK IN CORNWALL

In June and July 2023, the project performed a range of investigations and borehole testing in Cornwall to gather crucial data on the reservoir properties and characteristics of geothermal fluids deep underground. This information is vital for the potential future hosting of a demonstration extraction plant at United Downs, Cornwall. The pilot plant will serve as a testing ground for extraction technologies currently being developed by project partners.

Borehole tests were conducted at two previously drilled boreholes located near United Downs and the Cornish Lithium site on the United Downs Industrial Estate. The drilling rig required for equipment deployment arrived on 13 June and the tests were successfully completed on 7 July.

The scope of the work included hydrogeological testing and geochemical sampling of the fluids. Hydrogeological testing involves pumping the boreholes and injecting fluid through specially engineered tools to isolate the targeted geological structures. The collected samples are being analysed for their chemical constituents in order to characterise the fluids' Critical Raw Materials (CRM) content. The primary objectives of the tests at United Downs are to re-characterise the geochemistry within the permeable structures, confirm the maximum flow rates of the boreholes given the current configuration, undertake cross-well monitoring during flow-rate tests, determine aquifer properties and permeable structure continuity, and characterise hydraulic conditions.

Two specific testing techniques were utilised: airlift testing and tracer testing. During Airlift testing pressurised air was used to bring the fluid to the surface. The concurrent flow rate measurements allow to estimate the maximal production rates of the borehole. Tracer testing involves injecting an inert substance into the structure, allowing the determination of capacities and recharge mechanisms for the geothermal reservoirs. The team conducted a push-pull tracer test during which the tracer is injected into one borehole and subsequently back-produced from the same borehole, as well as a cross-well test, during which injection occurs in one borehole and production is performed at a second borehole. Tracer testing at United Downs showed that the fractured reservoir is extremely permeable with high ground-water flow, such that injected water is quickly replaced by reservoir fluids.

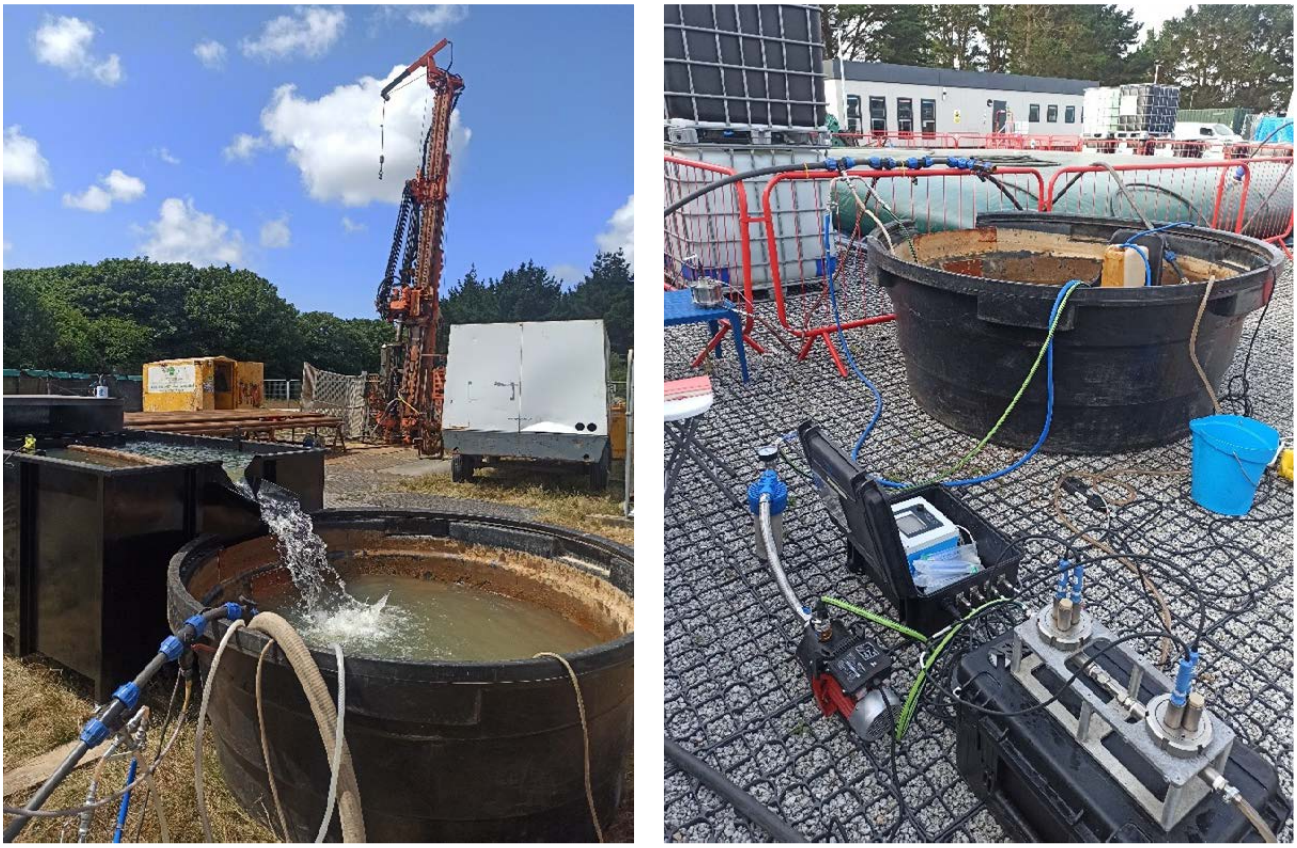

Fig. 2. Impressions from the hydraulic testing and chemical monitoring at United Downs, June 2023. Left: Drilling rig at the borehole GWDD001 in the background and fluid produced by airlift testing in the foregroud. Right: Chemical monitoring of produced fluid during tracer testing at GWDD002. In the foreground a flow-trought cell measuring pH, temperature, redox potential, electric conductivity, and direct oxygen.

CONCLUSIONS

The combined extraction technology will support the European Union in developing a more resilient and ethical CRM supply-chain from domestic sources, reducing its dependency on imports, which are exposed to market and political risks. The proposed solution will also help to bridge the gap between societal resistance to domestic raw materials extraction and increasing demand for raw materials that are critical for the Twin Transition. Finally, the combined extraction of minerals and heat will also increase the number of viable geothermal projects, fostering the green transition and diversifying Europe's energy portfolio.

CRITICAL RESOURCES AND POTENTIAL OF ESTONIAN PRECAMBRIAN AND PALEOZOIC ROCKS

by

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INTRODUCTION

Estonia boasts abundant mineral resources, including a century-long legacy of oil shale utilisation and potentially the largest phosphate resources in Europe. While some of these resources are well-studied, the others still need further exploration. Recent crises, spanning environmental, economic, and social realms, are reshaping perceptions of local resources across Europe. Consequently, there is an urgent need to thoroughly assess and optimise the use of the region's available resources in response to these evolving dynamics. In this context, we present a concise overview of Estonia's mineral resource potential, which plays a crucial role in fostering both the European Union's economy and security, as stipulated by the EU Critical Raw Material Act, as well as on a local scale within the Baltic and Nordic countries.

This overview has received support through the EGT-TWINN project, funded through the Horizon Europe program for research and innovation to the Geological Survey of Estonia. It will contribute to the development of multidisciplinary research and innovation in geological studies in Estonia by facilitating the collaboration of experts from leading international Earth Sciences research institutions in Finland, Denmark and UK.

BASICS OF GEOLOGY OF ESTONIA

Estonia is situated in the central part of the ancient Baltica paleocontinent, and thus being a part of the East European Craton. The Earth crust of the Baltica consolidated during the Svecofennian Orogeny in the Paleoproterozoic. The crystalline basement rocks are covered by Late Proterozoic (Ediacaran) to Lower Palaeozoic (Cambrian to Devonian) sedimentary rocks, with total thickness from 100 m (in the north) to 800 m (in the South and SW Estonia). The Precambrian rocks do not outcrop anywhere in Estonia and are known in the subsurface. The surface of the crystalline basement dips gently to the south. The boundary between the

Neoproterozoic crystalline rocks and the Palaeozoic sedimentary complexes extends along the seabed of the of the Gulf of Finland, separating Estonia and Finland.

METAL RESOURCES WITHIN THE LOWER PROTEROZOIC ROCK FORMATIONS

The Estonian Precambrian basement can be regarded as an extension of the rock complexes of the Fennoscandian Shield to the south. Consequently, it holds the potential for similar geological structures and metal formation as those found in Southern Finland and South-Central Sweden. In the Jõhvi crystalline rock complex of north-eastern Estonia and various locations in the northern part of the country, magnetite-gneisses are present. These gneisses contain magnetite (Fe_2O_3 ranging from 21.0 to 57 wt%) and occasionally a notable amount of manganese (up to 6 wt%). In earlier literature, these gneisses were referred to as "magnetite-quartzites," but it should be noted that the primary rock matrix for magnetite is garnet-pyroxene or garnet-amphibole-biotite gneiss, not quartzite.

Historical drilling activities have indicated that the Jõhvi complex of magnetite-rich rocks is up to 100 metres thick, with iron ore reserves (Fe content over 25%) estimated at around 350 million tons when calculated to a depth of 500 metres or 630 million tons when calculated to a depth of 700 metres. These estimates, however, are based on limited data and require further assessment through extensive exploration drilling in the future. A recent drilling campaign conducted from 2018 to 2020 did not significantly improve our understanding of the Jõhvi magnetite-rich rock deposit's size. Nonetheless, it did yield valuable insights into the mineralogy and geochemistry through the analysis of new drill cores. The mineralised magnetite-rich beds exhibit complex structural characteristics and encompass a wide variety of rock types. Magnetite and sulphide minerals are sporadically distributed across all rock types, but substantial mineralisation is primarily associated with specific rock types, including garnet-pyroxene, pyroxene-garnet, pyroxene gneisses, garnet-amphibole, amphibole-garnet, and biotite-amphibole gneisses (Soesoo et al. 2004, Soesoo et al. 2021, Nirgi & Soesoo 2021).

Sulphide mineralisation, comprising a combination of pyrite/pyrrhotite and minor occurrences of chalcopyrite, arsenopyrite, iron arsenide (loellingite), galena, and sphalerite, suggests a complex and potentially multiphase history of mineralisation within these rocks. Chalcopyrite is typically found alongside pyrite and pyrrhotite, whereas loellingite and arsenopyrite appear to be commonly associated with quartz-feldspar veining, occasionally containing gold and silver (Nirgi & Soesoo 2021). These Jõhvi rocks exhibit similarities to deposits in the Bergslagen ore provinces, Sweden, and potentially to the Orijärvi region, in Southern Finland. Furthermore, significant anomalies of sidero-chalcophile sulphide-graphite-bearing gneisses have been identified in other regions of Northern Estonia, where copper (Cu), lead (Pb), and zinc (Zn) contents can reach levels as high as 5.6%.

PHOSPHORUS AND RARE EARTH ELEMENTS IN ESTONIAN LOWER PALAEOZOIC PHOSPHORITES

Estonia holds potentially the largest unused sedimentary phosphate rock resources in Europe, having estimated to about 3 billion metric tons. There are three major phosphorite deposits – Rakvere, Toolse and Aseri, all located in northern Estonia. The massive accumulations of the phosphatised and REE-enriched

inarticulated brachiopod debris in varigrained sandstones deposited approximately 480–490 million years ago. The brachiopod shells and their debris may contain up to 35–37 wt% P_2O_5.

The phosphorite deposits were extensively studied during the Soviet time in 1960s–1980ies. Unfortunately, the "Phosphorite War" in 1980ies (a public rebellion against the phosphorite mining) impeded research and exploration of the phosphorite deposits in Estonia for almost 25 years after Estonia regained independence in 1991. Fortunately, there has been a shift in the political perspective on research of the Earth resources in the last five years. The mineral exploration geologists at the Geological Survey of Estonia recently completed a comprehensive report, assessing the historical geological-geochemical data with data obtained from analyses of 37 new drill cores (Joosu et al. 2023).

The latest geochemical studies have revealed an enriched, but very variable content of rare earth elements in the phosphatised brachiopod shells. For example, La content in brachiopod shells ranges 50–600 ppm, Ce–40–1300, Pr–4–170, Nd–20–850, Sm–3–200 and Gd–4–155 ppm. The total REEs (∑REE) can reach up to 3600–4000 ppm, ranging in average from 1000 to 2600 ppm in the brachiopod shells (Soesoo et al studies during 2012–2020; Soesoo et al. 2020). However, the large-scale geochemical study by Joosu et al. (2023) indicated that the average ∑REE concentrations in the raw ore were 364, 340 and 262 ppm for the Toolse, Aseri and Rakvere phosphorite deposits, respectively.

Therefore, the Estonian phosphorites are currently not deemed economically viable for standalone REE production. However, when considered as a co-product of the phosphate fertiliser production, REE extraction may become economically attractive within the current global socio-political-technological developments. Considering conventional mining operations with an annual production of 5 million metric tons of ore, the projected annual total REE yield could reach 720 tons at an average ∑REE of 1200 ppm (Soesoo et al. 2020). Additionally, approximately 120 tons of uranium and 27 tons of thorium can be extracted annually. Relying on the vast phosphorite resources in Estonia, the supply of both critical elements – phosphorus and REEs will benefit the EU economy and will alleviate the EU dependency on critical raw materials. In the end Estonia may become the leading actor in the European phosphate industry which contributes the national wealth as well.

ENERGY RESOURCES IN ESTONIA: A LEGACY AND A PATH FORWARD

Throughout the history, Estonia has relied heavily on one key energy resource – an oil shale, specifically the kukersite oil shale. The kukersite oil shale is a sedimentary rock which formed in the Late Ordovician age, approximately 460 million years ago. The kukersite oil shale mining holds a central role in the Estonian mining heritage, spanning over a century of mining history. The kukersite deposit in north Estonia stands out globally by a high quality: its organic matter content varies from 15% to 55%, the calorific value may be 15 MJ/kg (3,600 kcal/kg), and Fischer Assay oil yields ranges from 30% to 47%. The largest kukersite deposits in Estonia, particularly the Estonian and Tapa deposits, cover an extended area of approximately 3,000 km^2. To date, more than 1.2 billion tons of kukersite have been extracted, whereas the estimated total resource is about 4.63 billion tons.

Despite the impracticality of the direct oil shale combustion in power plants from economic and environmental perspectives in the future, Estonian oil shale has

been instrumental in maintaining the country's energy independence for several decades. However, it is evident that a revolutionary technological breakthrough is required within the oil shale sector to ensure energy independence for Estonia during the transitional period before the country, along with Europe and the wider world, transitions to more sustainable and eco-friendly energy sources for daily life. It is worth noting that kukersite may continue to serve as a vital raw material in the chemical industry's future endeavours.

In conclusion, Estonia's energy landscape has been shaped by the rich deposits of the kukersite oil shale – a resource that has sustained the nation for generations. As we look to the future, Estonia, like the rest of Europe and the world, faces the imperative to transition to cleaner and more sustainable energy sources. The legacy of kukersite mining provides a foundation for future innovation and adaptation, as Estonia seeks to forge a path toward a greener and more energy-efficient future while preserving its energy independence.

ESTONIAN LOWER PALAEOZOIC BLACK SHALE: A CRITICAL METAL RESOURCE

While the Estonian kukersite is low in all kinds of metals, which is essential for combustion in power plants, there is also another type of oil shale in Estonia – known as a black shale (also a term graptolite argillite is used for this particular black shale). Estonian graptolite argillite is of sapropelic origin and is characterised by high concentrations of several metals, for instance: U (up to 1200 ppm), Mo (1000 ppm), V (1600 ppm), Ni as well as by the other heavy metals. The calorific value of this rock ranges from 4.2–6.7 MJ/kg and the Fischer Assay oil yield is 3–5%. During the Soviet era, the graptolite argillite was mined for uranium production in the vicinity of Sillamäe town, NE Estonia.

Between 1964 and 1991, approximately 73 million tons of graptolite argillite was removed as an overburden of the phosphorite bed and piled into waste heaps at Maardu phosphorite opencast pit, near Tallinn. The estimated resource of the Estonian graptolite argillite rock is about 65–70 billion tons (Hade & Soesoo 2014). The estimated tonnage of zinc in the Estonian black shale is 16.5330 Mt, vanadium - 47.7538 Mt and molybdenum - 12.7616 Mt. The western part of Estonia has the highest potential for these elements, especially for U and Mo production. It should be noted that due to the fact that the Estonian black shale overlies the phosphorite ore in the geological section, the further mining of the phosphorite ore will be a challenging and complex task.

THE PALAEOZOIC CARBONATE ROCKS – LIMESTONES AND DOLOSTONES

The Ordovician and Cambrian sedimentary rocks in Estonia which formed approximately 470 to 360 million years ago are mostly carbonate rocks – limestones and dolostones. Both dolostone and limestone have played and continue to play significant roles as valuable natural resources in Estonia, serving both the various local needs as well as being export commodities. Historically, these carbonate rocks were used in the building construction. In medieval ages the usage of carbonate rocks increased remarkably, and they became the main construction material in building castles as well as the whole medieval towns. The carbonate rocks from

coastal quarries of Estonia were exported, for instance, to Germany, Russia, Latvia and to the Nordic countries.

The dolostone (subcategorised into technological, construction, filling, and other uses), was extracted from 37 mines in 2021, totalling 834 thousand cubic metres. Most of the mined dolostone was used as aggregate in the construction business. As of December 31, 2021, the actively usable dolostone reserves in Estonia were estimated at 100,940 thousand cubic metres. It's worth noting that dolostone has a potential application in metallic magnesium extraction.

Limestone, on the other hand, was extracted from 61 mines, amounting to approximately 2,491 thousand cubic metres. A significant share of the extracted limestone was used for various construction works. As of December 31, 2021, active limestone resources in Estonia were estimated at 245,310 thousand cubic metres. These figures are provided by the Estonian Land Board 2022 (www.maaamet.ee).

CONCLUSIONS

- Several metal occurrences are known in the Paleoproterozoic crystalline basement of Estonia. The magnetite-gneisses and gneisses enriched in Mn (up to 6 wt%) are found in the Jõhvi crystalline rock complex in NE Estonia, as well as in several other locations elsewhere. Historical magnetite ore resource estimates suggest that the total ore tonnages exceed 300 million tons.
- Estonia probably holds the largest in Europe, but so far unmined sedimentary phosphate rock resource, equalling to about 3 billion metric tons. The ore is relatively enriched by rare earth elements.
- The phosphates are overlain by metal-enriched black shale – the graptolite argillite. The shale can be the source for several critical and other useful elements, such as vanadium, zinc, molybdenum, uranium, led.
- The main energy and chemical industry resource in Estonia is the kukersite oil shale which reserves are estimated to be about 4.627 billion tons.
- The carbonate rocks are largely used as an aggregate for building purposes in Estonia. The dolostone mining in 2021 was about 834 thousand m^3 and the limestone was extracted in an amount of 2491 thousand m^3.

REFERENCES

Estonian Land Board 2022. Koondbilanss seisuga 2021. Available at: https://geoportaal.maaamet.ee/docs/geoloogia/koondbilanss_2021.pdf?t=20220605194101

Hade, S. & Soesoo, A. 2014. Estonian graptolite argillites revisited: a future resource? Oil Shale 31, (1), 4–18.

Joosu, L, Vind. J., Lumiste, K. Polikarpus, M., Tarros, S., Pärn, J., Kansi, K., Tamm, K., Bauert, H., Kaasik, T., Kurvits, K., Nemliher, J.† & Kuldkepp, R. 2023. Exploration of phosphorite and black shale in North-Eastern Estonia. Rakvere: Geological Survey of Estonia.

Nirgi, S. & Soesoo, A. 2021. Geology and geochemistry of a Paleoproterozoic iron mineralization in North-Eastern Estonia. Proceedings of the Karelian Research Centre of the Russian Academy of Sciences (10), 25–43.

Soesoo, A., Nirgi, S., Urtson, K. & Voolma, M. 2021. Geochemistry, mineral chemistry and pressure–temperature conditions of the Jõhvi magnetite quartzites and magnetite-rich gneisses, NE Estonia. Estonian Journal of Earth Sciences (70), 71–93.

Soesoo, A., Puura, V., Kirs, J., Petersell, V., Niin, M. & All, T. 2004. Outlines of the Precambrian basement of Estonia. Proc. Estonian Acad. Sci. Geol. (53), 149–164.

Soesoo, A., Vind, J. & Hade, S. 2020. Uranium and thorium resources of Estonia. Minerals (10), 798.

REE CONTENTS OF ESTONIAN PHOSPHORITES: INSIGHTS ON POTENTIAL RESOURCES FOR EU CRITICAL RAW MATERIALS

by

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The increasing demand for clean technologies has a major impact on the demand for rare earth elements (REE) (Lucas et al. 2014). Sedimentary phosphorites have recently been highlighted as a potential economic source of REE as P_2O_5 by-products (Balaram 2022). The Ordovician shelly phosphorites of Estonia are among Europe's most extensive phosphate rock reserves, with a tonnage approximately of three billion metric tonnes (Bauert et al. 2015). Assessing REE resources and these deposits' enrichment model would help secure sustainable and responsible European sources.

Shelly phosphorites are low-grade, high-volume deposits composed of fragments of brachiopods in sandstone, sometimes cemented by carbonates. A detailed geochemical high-resolution investigation was conducted in the Toolse deposit through the entire Kallavere formation, composed of three members: Katela, Suurjõgi and Maardu (Graul et al. 2023). REE+Y patterns showed a downward enrichment following the occurrence of shell beds. The most prevalent REEs are, in order, Ce, Y, Nd, and La, which respectively reach maximum mean values of 296 ppm, 248 ppm, 164 ppm and 135 ppm, per 10 cm horizons. Toxic element contents (U, Th, Zr and Cd) were below 20 ppm. In the lower part of the deposit, the ∑REE+Y concentration is enriched up to 12-fold, compared to the average shale (PAAS), reaching up to 1234 ppm. Shale-normalised REE+Y patterns were homogeneous throughout the deposit except for the cerium and yttrium contents.

The $REE+Y_{SN}$ contents of the phosphorites indicate a distinctive 'bell-shaped' pattern enriched with middle-REE (MREE). Carbonated cement was found to be depleted. REE enrichment occurred as multistage enrichment associated with steep redox gradients in porewater, plenished by upwelling currents. Positive Y anomalies indicate an initial uptake of REE + Y in an oxic environment near the sediment–water interface. The transition to a suboxic environment resulted in the dissolution of Mn-(oxyhydr)oxides and the release of LREE in the system, leading to an overprint of the original REE pattern. A late enrichment in MREE occurred during early diagenesis due to the desorption of REE from the Fe-(oxyhydr)oxides and organic-rich particles under anoxic conditions (Graul et al. 2023).

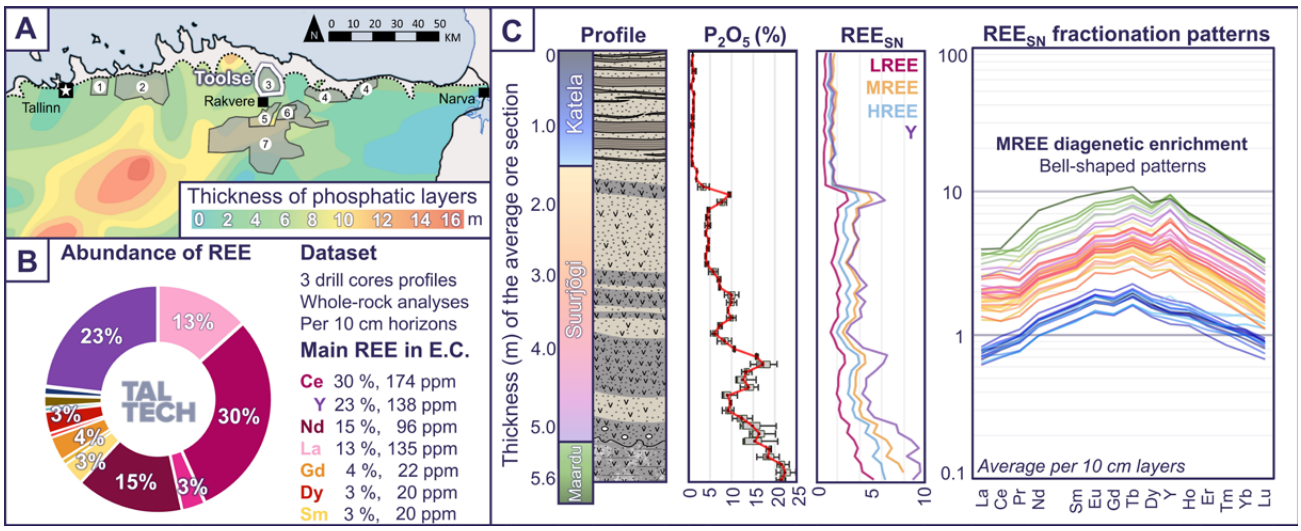

Fig. 1. a) Ore bodies and thickness of phosphatic layers. 1. Maardu, 2. Tiskre, 3. Toolse, 4. Aseri-Saka, 5. Rägavere, 6. Kabala, 7. Rakvere. b) Abundance of REE. C. Average P_2O_5 and REEs trend with depth and fractionation patterns.

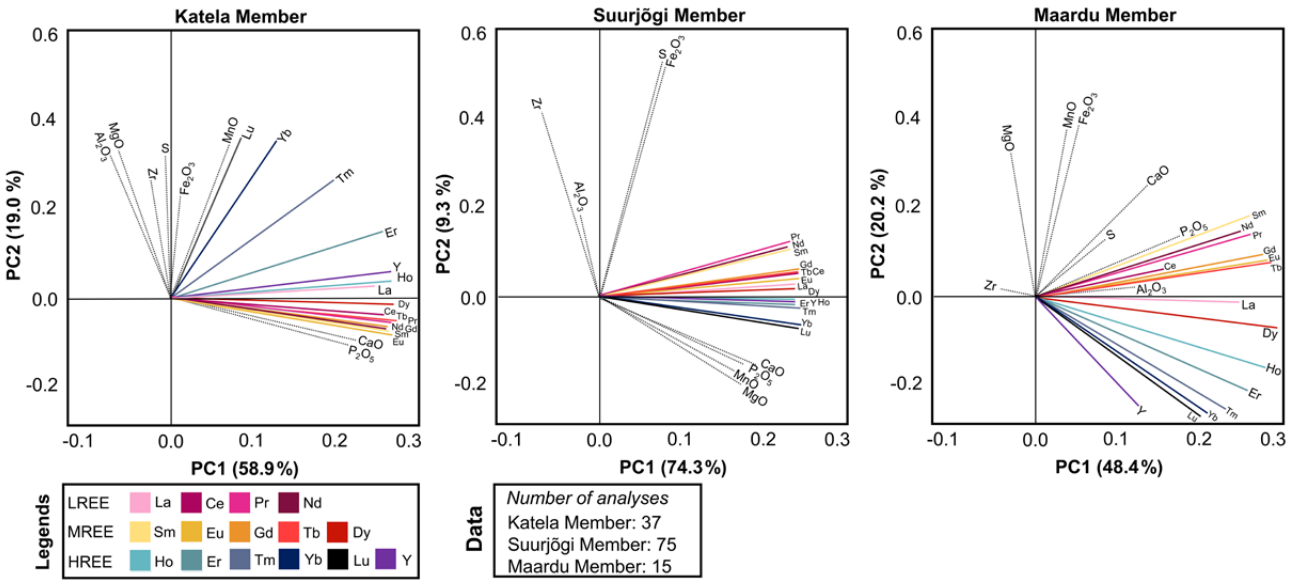

Fig. 2. Principal component analyses (PCA) for each member of the Kallavere Formation. The first principal component (PC1) accounts for 19.0% in the Katela Member, 9.3% in the Suurjõgi Member and 20.4% and in the Maardu Member for data variability. The second principal component (PC2) accounts for 58.9%, 74.3% and 48.4%, respectively.

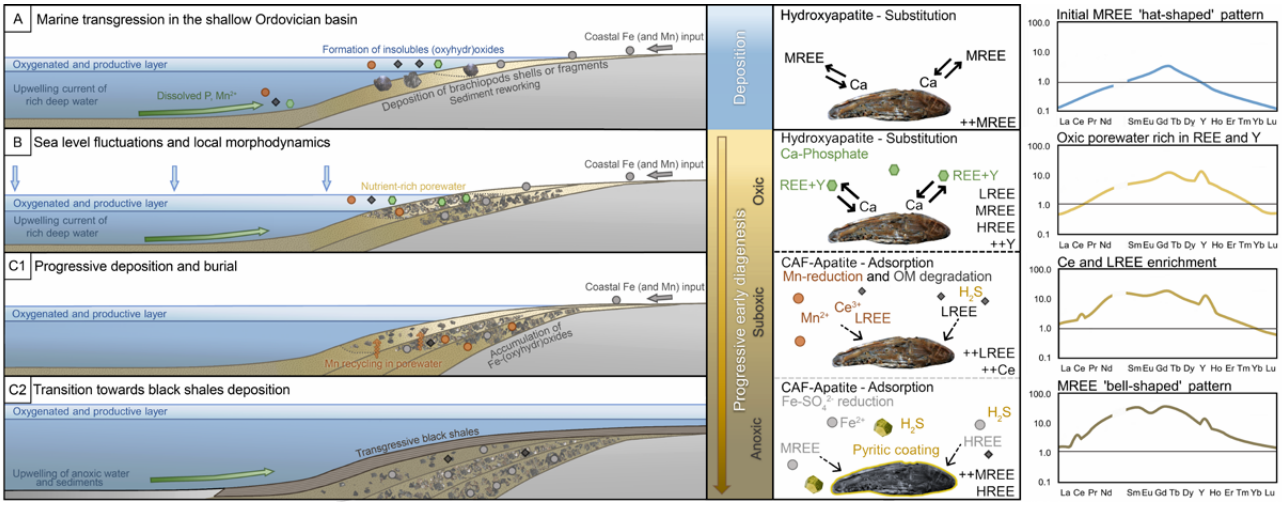

Fig. 3. General depositional-geochemical model proposed for the Toolse phosphorites.

a) Upwelling of deep-water rich in precursor carrier phases of REE+Y and transport of brachiopods to the nearshore. The deposition of the first shell beds. At this stage, the shells are comprised of hydroxyapatite-like bioapatite and MREE cationic exchange via the substitution mechanism leads to the development of the 'hat-shaped' REE pattern.

b) The shells or fragments are burrowed close to the SWI and in contact with the oxic porewater, which supports a pervasive uptake and a positive yttrium anomaly.

c1) Progressive burial of sediments and a relatively rapid transition to suboxic conditions due to the breakdown of organic matter induces the desorption of Ce^{3+} and other LREE from Mn-(oxyhydr)oxides and release to the pore water. Enrichment of LREE is proportional to the local availability of Mn-(oxyhydr)oxides. The transformation of hydroxyapatite into carbonate fluorapatite involves a change in REE uptake mechanism, from substitution to adsorption. The Fe-(oxyhydr)oxides accumulated in the sediment start to dissolve and pyrite precipitates in shell-induced micromillieu.

c2) The lower sedimentary column is under anoxic conditions, allowing the Fe-(oxyhydr) oxides reduction, general diagenetic MREE enrichment in apatite and acquiring the 'bell-shaped' REE pattern. The upwelling of oxygen-depleted nutrient-rich water leads to the deposition of transgressive black shales over the phosphatic sandstones.

REFERENCES

Balaram, V. 2022. Rare Earth Element Deposits: Sources, and Exploration Strategies. Journal of the Geological Society of India 98(9), 1210–1216. Available at: https://doi.org/10.1007/s12594-022-2154-3

Bauert, H., Soesoo, A. & Hade, S. 2015. Strategic raw materials of Estonia. Rakvere: Eesti strateegilised maavarad.

Graul, S., Kallaste, T., Pajusaar, S., Urston, K., Gregor, A., Moilanen, M., Ndiaye, M. & Hints, R. 2023. REE+Y Distribution in Tremadocian Shelly Phosphorites (Toolse, Estonia): Multi-Stages Enrichment in Shallow Marine Sediments during Early Diagenesis. Journal of Geochemical Exploration 254, 107311. Available at: https://doi.org/10.1016/j.gexplo.2023.107311

Lucas, P., Lucas, J., Le Mercier, T., Rollat, A. & Davenport, W. G. 2014. Rare Earths: Science, Technology, Production and use. Elsevier Inc. Available at: https://doi.org/10.1016/C2012-0-02577-X

THE GREENPEG PROJECT TOOLSET TO EXPLORE FOR BURIED PEGMATITES HOSTING RARE METALS AND HIGH PURITY QUARTZ TO FEED THE ENERGY TRANSITION

by

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GREENPEG, a European innovation project financed by the European HORIZON 2020 programme, is developing new and improved exploration approaches for niobium-yttrium-fluorine (NYF) and lithium-caesium-tantalum (LCT) pegmatite ores in different European settings (wall rocks, vegetation, topography). The aim is to increase exploration success and reduce associated environmental and social impacts. To this end, GREENPEG is delivering an integrated, multi-method, sustainable and low-cost toolset to explore for buried pegmatites including two new exploration datasets and workflows, and three new instrumental exploration techniques and devices.

Granitic pegmatites, the target of the GREENPEG exploration toolset, can be economically enriched in a variety of critical and other rare metals (Bradley et al.

2017, Linnen et al. 2012, London 2016), industrial minerals (Glover et al. 2012) and gemstones (Simmons et al. 2012) and are thus strategically important exploration targets. The commodities we focused on are lithium and high-purity quartz, which are in increasing demand for Li-ion batteries used in electric vehicles and other devices and for photovoltaics, respectively.

Pegmatite deposits are common in Europe but are an underexplored resource (e.g. Gourcerol et al. 2019). A few are mined in Europe for Li, Be, Ta and ceramic feldspar (Portugal, Finland, France), and quartz (Norway), but there is huge potential to find more. Increasingly, exploration is for concealed deposits as most exposed and near surface examples have already been discovered. This presents a challenge however as pegmatites are usually invisible or indistinct in geophysical surveys as they are insufficiently conductive or magnetic and may not have an adequately high density to create a measurable contrast with their host rocks (Trueman & Černý 1982, Galeschuk & Vanstone 2005, 2007, Selway et al. 2005, Bradley et al. 2017).

The new toolset consists of a complementary suite of adjusted conventional and newly invented methodologies and new data processing approaches optimised for the relatively small size, mineralogy, chemistry and petrophysics of pegmatite deposits, and a range of European surface environments. Its development is based on a modified genetic model for European pegmatite deposits by Müller et al. (2022) and a multi-scale (province-, district- and prospect) and multidisciplinary approach. By improving the targeting of pegmatite deposits, and thus the effectiveness of exploration, the delivered toolset will reduce exploration time and costs, the level of environmental disturbance from the use of relatively invasive techniques, and social impacts such as noise. The toolset developed has been adjusted, optimised and tested for commercialisation under Technical-Readiness-Level-7 conditions in three European demonstration and exploration brown field sites: Wolfsberg in Austria, Leinster in Ireland, and Tysfjord in Norway. The toolset encompass a wide array of technologies, including satellite image processing and both airborne and ground-based geophysics and geochemical approaches and three new instrumental demonstrations to effectively identify buried (up to 100 m depth), small (10,000 - 1,000,000 m^3) and clustered pegmatite ore bodies.

Some highlights of the GREENPEG toolset are:

- The demonstration deployment of the first European EASA certified helicopter-compatible nose stinger magnetometer which will allow lower altitude airborne surveys (down to about 50 m above ground), with a close flight line distance. This system allows to acquire simultaneously high-resolution magnetic and radiometric data in areas of varying topography and vegetation, such as in certain parts of the Alps and Scandinavia (Wolfsberg and Tysfjord demonstration sites, respectively). It replaces the existing magnetic bird system hanging 30 m below the helicopter, which has to be flown high producing low resolution even more for radiometrics than for magnetics.
- Technological developments in drone-borne hyperspectral imagery which increasingly close the gap between airborne- and ground-based data. Hyperspectral imagery is on the rise and shows potential for mapping of mineral resources. Drones will also replace more costly airborne geophysics if drone specific operation conditions like visual line of sight and tree height etc. are given. Drone-borne systems have the advantages of being relatively low cost, easily deployable, have a short turn-around time and are quieter. This means that they can operate at relatively low levels so reducing noise emissions and have the capacity to acquire higher resolution data.

- A relatively low cost piezoelectric spectrometer demonstration for rapid and efficient detection of buried pegmatite ore bodies is an integrated part of the toolset. The instrument is based on a concept developed and successfully deployed in the former Soviet Union and Canada to explore for gold-bearing quartz veins and pegmatites (e.g., Neishtadt & Eppelbaum 2012). It utilises the strongly piezoelectric nature of pegmatites (specifically quartz). This method, however, has very rarely been used in exploration although despite being the only technique that directly accesses a specific petrophysical characteristic of most pegmatites.
- The first freely available petrophysical database for pegmatite ores has been established which will allow geophysical exploration methods to be adjusted and applied more successfully (Haase & Pohl 2022). Based on these and other data, GREENPEG will provide algorithms optimised for the sizes and depths of European pegmatite ore bodies, which will result in the production of high-precision 3D fertility maps.
- Construction of a freely available library of spectral reflectance for pegmatite minerals and ores which can be used easily by small and medium sized enterprises to process satellite images (Cardoso-Fernandes et al. 2022).
- The new trace-element-in-quartz assessment tool which aims to establish the district scale chemical zoning of pegmatite fields from the Al, Li, Ge and Ti concentrations of pegmatite quartz will be established. This geochemical mapping will allow vectoring, in combination with other methods, towards areas to areas with highest ore potential and quality.
- Using recently enhanced methods for combined mineralogical, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) trace element micro-mapping, and whole-sample geochemical analysis, GREENPEG will provide tools for textural and geochemical pegmatite source discriminations for heavy and other resistant pathfinder minerals in soils and stream sediments.

These inventions and optimisations will be integrated and upscaled by GREENPEG into a marketable toolset to target European pegmatite ores. The toolset will be easily deployable by small and medium sized enterprises and accessible to exploration and mining companies in "strategic knowledge-based consultancy services", offered by GREENPEG partners, and via publications. They will facilitate – for an affordable price and in a sustainable way – the mapping of zones containing potentially economic pegmatites and provide exploration vectors towards mineralised ore bodies to maximise the success of subsequent more costly exploration methodologies such as drilling.

REFERENCES

Bradley, D. C., McCauley, A. D. & Stillings, L. M. 2017. Mineral-deposit model for lithium-cesium-tantalum pegmatites. U.S. Geological Survey Scientific Investigations Report 2010–5070–O. 48 p. Available at: https://doi.org/10.3133/sir201050700

Cardoso-Fernandes, J., Santos, D., Rodrigues de Almeida, C., Lima, A., Teodoro, A. C. & GREENPEG project team 2022. Spectral Library of European Pegmatites, Pegmatite Minerals and Pegmatite Host-Rocks – The GREENPEG Project Database. Earth System Science Data Discussion 2022, 1–19. Available at: https://doi.org/10.5194/essd-2022-386

Galeschuk, C. R. & Vanstone, P. J. 2005. Exploration for buried rare element pegmatites in the Bernic Lake region of southeastern Manitoba. In: Linnen, R. L. & Samson, I. M. (eds) Rare-Element Geochemistry and Mineral Deposits. Geological Association of Canada Short Course Notes 17, 159–173.

Galeschuk, C. R. & Vanstone, P. J. 2007. Exploration techniques for rare-element pegmatite in the Bird River Greenstone Belt, Southeastern Manitoba. In: Milkereit, B. (ed.) Proceedings of Exploration 07: Fifth Decennial International Conference on Mineral Exploration, 823–839.

Glover, A. S., Rogers, W. Z. & Barton, J. E. 2012. Granitic pegmatites: Storehouses of industrial minerals. Elements 8, 269–273.

Gourcerol, B., Gloaguen, E., Melleton, J., Tuduri, J. & Galiegue, X. 2019. Re-assessing the European lithium resource potential – A review of hard-rock resources and metallogeny. Ore Geology Reviews 109, 494–519.

Haase, C. & Pohl, C. M. 2022. Petrophysical Database for European Pegmatite Exploration–EuroPeg. Minerals 12, 1498. Available at: https://doi.org/10.3390/min12121498

Linnen, R. L., Van Lichtervelde, M. & Černý, P. 2012. Granitic pegmatites as sources of strategic metals. Elements 8, 275–280.

London, D. 2016. Rare-element granitic pegmatites. In: Verplanck, P. L & Hitzman, M. W. (eds) Rare Earth and Critical Elements in Ore Deposits. Reviews in Economic Geology 18, 165–194.

Müller, A., Reimer, W., Wall, F., Williamson, B., Menuge, J., Brönner, M., Haase, C., Brauch, K., Pohl, C., Lima, A., Teodoro, A., Cardoso-Fernandes, J., Roda-Robles, E., Harrop, J., Smith, K., Wanke, D., Unterweissacher, T., Hopfner, M., Schröder, M., Clifford, B., Moutela, P., Lloret, C., Ranza, L. & Rausa, A. 2022. GREENPEG – Exploration for pegmatite minerals to feed the energy transition: First steps towards the Green Stone Age. In: Smelror, M., Hanghøj, K. & Schiellerup, H. (eds) The Green Stone Age: Exploration and Exploitation of Minerals for Green Technologies. London: Geological Society, Special Publications 526. Available at: https://doi.org/10.1144/SP526-2021-189

Neishtadt, N. M. & Eppelbaum, L. V. 2012. Perspectives of application of piezoelectric and seismoelectric methods in applied geophysics. Russian Geophysical Journal 51–52, 63–80.

Selway, J. B., Breaks F. W. & Tindle A. G. 2005. A review of rare-element (Li-Cs-Ta) pegmatite exploration techniques for the Superior Province, Canada, and large worldwide tantalum deposits. Exploration and Mining Geology 14, 1–30.

Simmons, W. B., Pezzotta, F., Shigley, J. E. & Beurlen, H. 2012. Granitic pegmatites as sources of coloured gemstones. Elements 8, 281–287.

Trueman, D. L. & Černý, P. 1982. Exploration for rare-metal granitic pegmatites. In: Černý, P. (ed.) Granitic Pegmatites in Science and Industry. Mineralogical Association of Canada, Short Course Handbook 8, 463–493.

SEMACRET – RESPONSIBLE EXPLORATION FOR GREEN TRANSITION CRITICAL RAW MATERIALS

by

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SEMACRET is a project co-funded by the European Union and UKRI (SEMACRET, GA101057741) that aims to develop socially and environmentally responsible exploration means for green transition (Critical) Raw Materials (CRMs), including Ni, Cu, Co, V, Ti, Cr, and platinum-group elements (PGE), hosted by ultramafic-mafic orthomagmatic mineral systems. The primary focus of this project includes refining geological knowledge of ore-forming processes following the mineral systems approach, optimising regional-scale exploration targeting, and providing integrated solutions to target ore bodies efficiently on the local scale.

Geological modelling of ore-forming processes per the mineral systems approach includes analysis of the magma sources, modelling the pathways architecture for magma transport system and metal deposition mechanisms. For magma source, there is controversy on the source mantle of the large volumes of mafic-ultramafic magma (Barnes et al. 2016, Fig. 1). Re-Os, Sm-Nd isotopic systems are robust tools to distinguish different mantle sources. A database of isotope geochemistry of large igneous provinces with ages spanning from Archean to Paleozoic is being created, utilising existing data from literature. Sampling and geochemical analyses are ongoing in Finland, Czechia and Portugal to supplement available data. Preliminary results show that most large igneous provinces and mafic intrusions have chondritic or positive γOs isotope composition, especially for the most primitive rocks. This indicates that the contribution of the sub-continental lithospheric mantle (SCLM) is insignificant, and the major mantle source is from plume or asthenospheric mantle. This inference is further supported by geochemical and thermodynamic modelling of plume magmatism in Fennoscandia (Guo et al. 2023). Pathways architecture is being modelled through mathematical modelling, which supports magma underplating and intermediate magma chambers (Fig. 1). The process of magma contamination and assimilation is studied using petrological analysis and thermodynamic simulations, investigating the effects of magma contamination on ore deposition, especially triggered by the assimilation of anhydrite and black shale. High-temperature experimental studies are being conducted to explore the interaction between sulphur-bearing rocks and magma (Fig. 1).

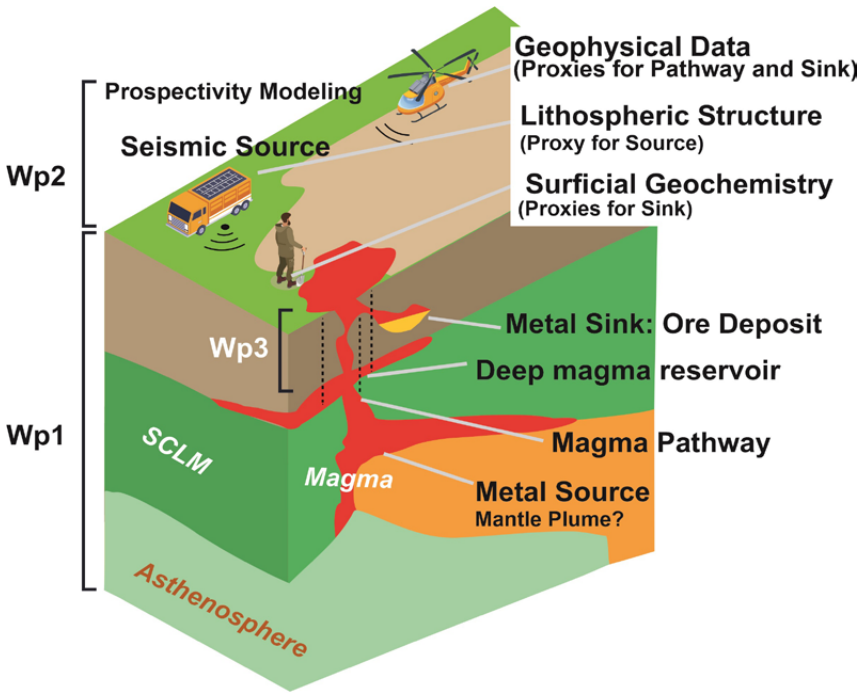

Fig. 1. Mineral systems approach and regional prospectivity modelling.

Regional exploration targeting of orthomagmatic mineral deposits at a regional scale involves the compilation of mineral system models for Ni-Cu-rich conduit type and PGE-Cr-rich layered mafic intrusion systems, supplemented by the insights gained from geological modelling (Fig. 1). These models compile all the crucial ore-forming processes of each mineral system, such that in the absence of even one of the processes, the deposit would not form. Targeting models are then generated based on the respective mineral system models identifying the targeting criteria dedicated for the reference study area, the Lapland belt in northern Finland, considering the datasets available and the scale of the study. Openly available public-domain geophysical datasets distributed by the Geological Survey of Finland (GTK) were utilised for the analysis to demonstrate the widespread applicability of the workflow. Spatial data processing and GIS analysis tools are then used to process primary geoscience data to map spatial proxies of each of the targeting criteria in the targeting model in the form of predictor maps. These predictor maps are then integrated using Fuzzy Inference Systems (FIS), a knowledge-driven, symbolic artificial intelligence-based integrating algorithm, to generate prospectivity maps (Porwal et al. 2015, Fig. 2). Two-stage FIS are employed, structured on the mineral systems model in which the first stage consists of a series of FIS were used to generate fuzzy prospectivity maps for individual components of the mineral system, namely, sources, pathways and traps, combining their respective fuzzy predictor maps. In the second stage, the fuzzy prospectivity maps of the individual components were combined using the product operator to generate the final mineral prospectivity maps (Fig. 2). The preliminary results show good agreement with the spatial pattern of known occurrences. High prospective areas are identified in the north-central and western part of the study area for further detailed scale exploration to narrow down target areas for eventual ground exploration.

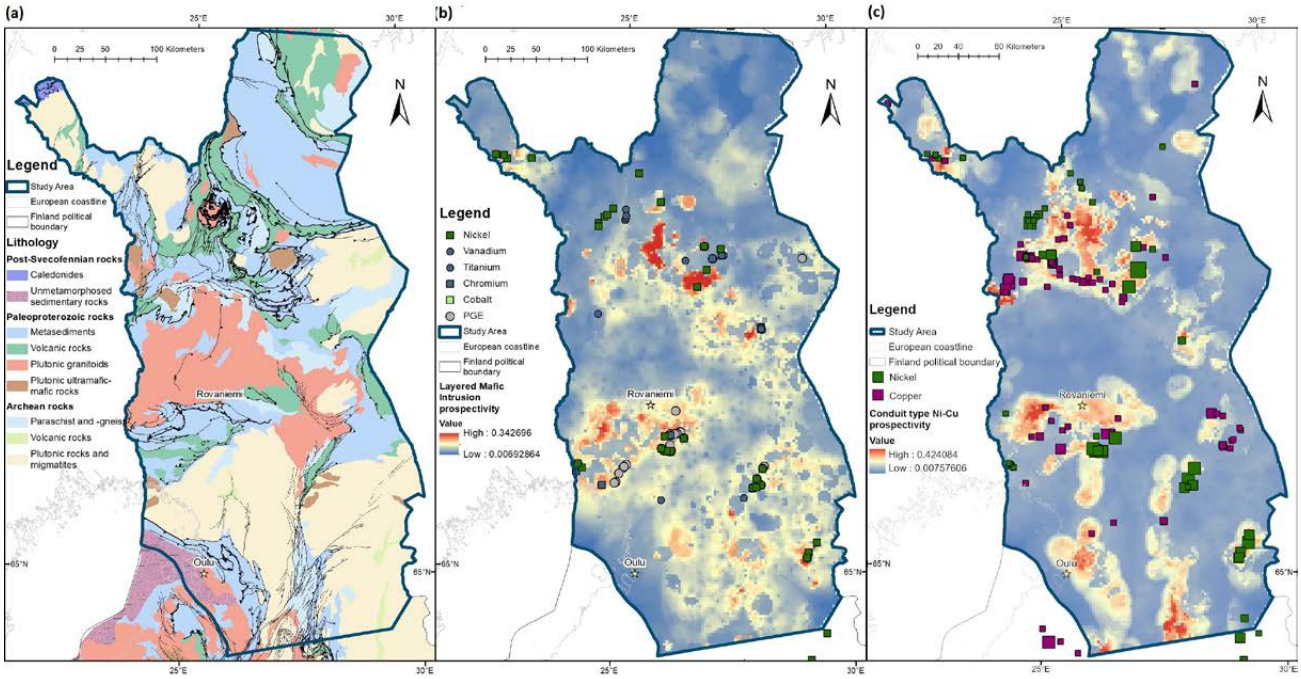

Fig. 2. Preliminary results of prospectivity modelling done as part of WP2. a) geology of the study area in northern Finland, b) prospectivity map for layered mafic intrusion related mineralisation, c) prospectivity map for conduit-type mineralisation. Metal occurrences include all known magmatic occurrences.

Besides the commonly used geodata, this project also involves parallel tasks to generate novel data sources and new proxies to be used in the prospectivity model, especially considering deeper geological processes in the mantle and deeper crustal level. A critical feature of large igneous provinces is the presence of a high-velocity, high-density lower crust (Alghamdi et al. 2018). This crust is interpreted as a signature of magmatic underplating, which could be remnants of deep reservoirs feeding shallower magma chambers. The seismic data interpretation further supports this. Thus, intermediate magma staging chambers, seen as magma underplating along the Moho boundary in tomography, and lower crustal thickness are considered a proxy for pathways architecture. The orthomagmatic mineral systems addressed in this project have a strong relationship with lithospheric structure and craton margins (e.g., Boscaini et al. 2022). However, lithospheric structure is often interpreted and subject to uncertainty, whereas the structure detected by geophysics represents present-day structure, which may differ from what existed at the time of mineralisation. To alleviate this problem, Lu-Hf isotopes are being used to map basement rocks and constrain lithospheric structure. Available data from literature has been compiled and interpreted. Furthermore, new zircon samples have been collected and are being analysed for Lu-Hf analysis, as well as Sm-Nd and U-Pb age determinations, to append the compiled database. Surficial till geochemistry is a significant proxy for metal deposition and preservation processes and has been instrumental in discovering many Finnish deposits. New research is being conducted in the analysis of surficial till geochemistry to improve the quality of interpretations. This task addresses the data variability problems, cleaning the dataset of erroneous values and the application of compositional data analysis (CoDA). In this effect, a new robust algorithm has also been developed to identify spatial outliers. Details of this task can be obtained in the dedicated abstract and poster submitted to the super-clustering event (Kalubowila et al. 2023).

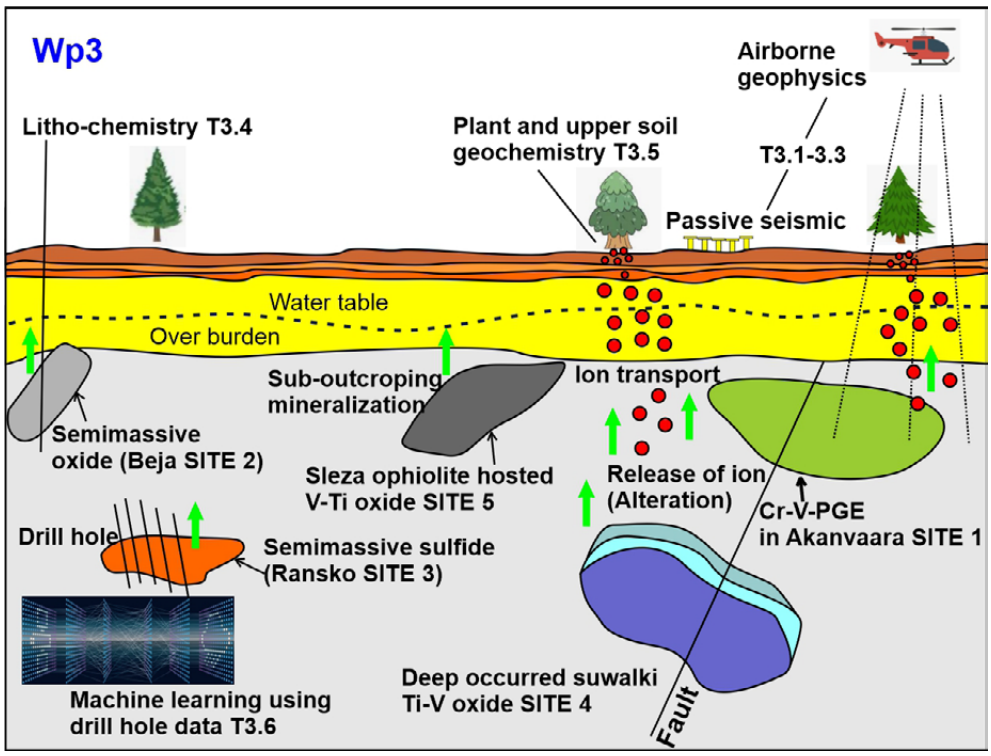

Fig. 3. Local scale exploration integrating different methods as solutions.

Local-scale exploration focuses on creating an integrated solution that combines innovative methods to identify high potential areas at the local deposit scale to be applied in brownfield exploration. Five known deposits in the EU are being used as reference sites. Different mineralisation styles of the orthomagmatic deposit group pose challenges and require different methodologies. We explore optimised solutions combining different methods for different mineralisation styles. These include combining airborne electromagnetic surveys (AEM), audiomagnetotelluric (AMT) and full tensor magnetic gradiometry (FTMG) to constrain the deep occurrence of oxide ores better; 3D inversion for electromagnetic data of sulfide ores; using passive seismic to constrain the local structure and surficial geochemical data interpretation; integrating airborne and ground induced polarisation (IP) for oxide ores (Fig. 3). Surveys have been planned and executed in several areas to collect new data, covering known mineralisation and potential nearby areas (Fig. 4). FTMG and AEM surveys are being carried out at Ransko in Czechia (Fig. 4). AEM and magnetic data has been acquired at Beja in Portugal, and a ground IP survey has been planned for joint inversion (Fig. 4). Magnetic and IP measurements have been carried out at Ślęża in Poland, along with pXRF measurements. At Suwalki in Poland, AMT and FTMG have been conducted to detect V-Ti oxide mineralisation at depth (Fig. 4). In Finland, at Akanvaara, AEM, AMT, IP and magnetic surveys have been conducted (Fig. 4). Besides the new data, archived petrophysical and geophysical data in many of these regions is being digitised and reinterpreted. Furthermore, new and improved algorithms are being developed for the processing and interpretation of EM and IP data, to be publicised as QGIS plugins.

Novel environmentally friendly surficial geochemistry tools based on CoDA for upper soil horizons and plant geochemistry are being explored. Preliminary data analysis and interpretation of upper soil samples in Akanvaara has been completed, and plant and upper soil samples have been collected in three reference sites. Data processing, compositional data analysis and interpretation are currently ongoing.

Additionally, 3D prospectivity modelling is being carried out, especially in areas with extensive drill core data, to detect new mineralisation horizons within the known deposits. This involves the creation of 3D geological models based on the drill core data. Furthermore, the 3D geological model and borehole data are also being used for resource modelling using machine learning. This task aims to develop novel, machine learning-based techniques to interpolate resources between adjacent boreholes.

In addition to exploration technique development, SEMACRET promotes **social awareness** of raw materials exploration and mining. It aims to investigate the influence of citizens› knowledge levels on their attitudes and acceptance of mineral exploration through community events, interviews and social media analysis using artificial intelligence. This aspect of the project is detailed in a dedicated abstract and presentation at the super clustering event (Bahr et al. 2023).

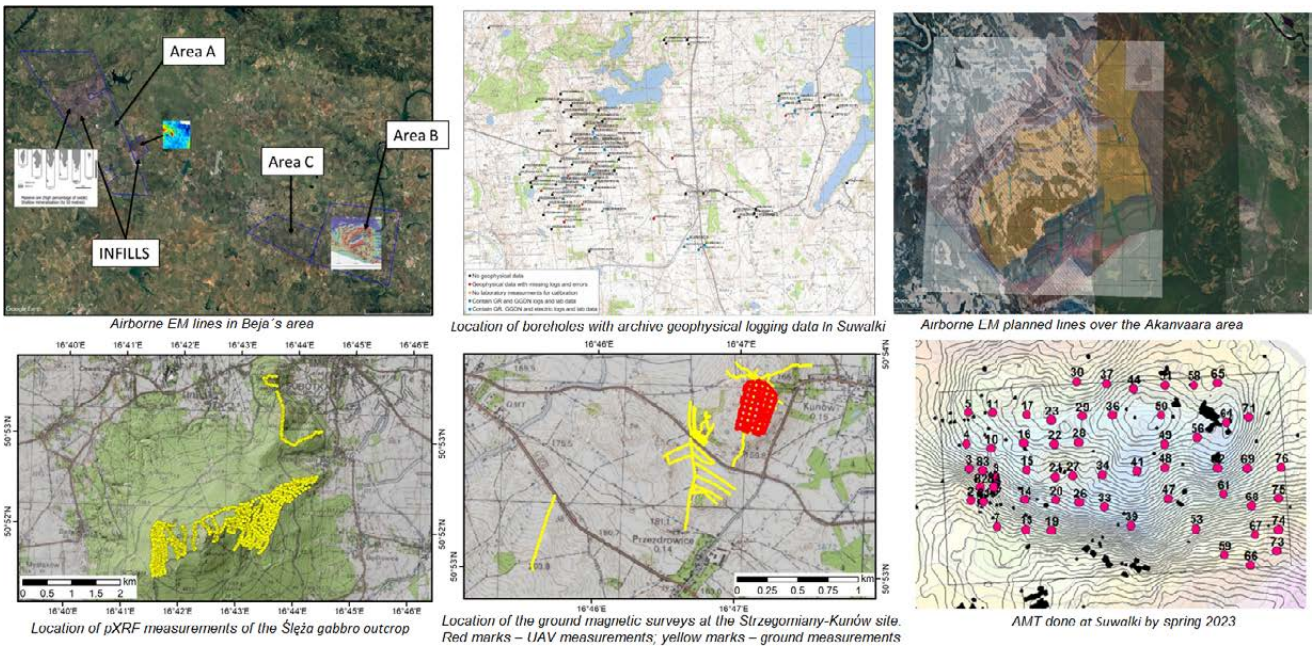

Fig. 4. Graphic summarising the progress achieved in the geophysical surveys planned in the five reference sites of the SEMACRET project.

This project also addresses estimating and reporting critical mineral resources to assess exploration and production potential. A key challenge lies in the diverse reporting methods used by different countries, with some using national standards instead of internationally recognised ones like the Joint Ore Reserve Committee (JORC) code. We intend to apply the United Nations Framework Classification (UNFC) code and the United Nations Resource Management System (UNRMS) system to categorise various mineral resource types within orthomagmatic ore deposits. Planning and preliminary preparation for the construction of a database have been initiated.

REFERENCES

Alghamdi, A. H., Aitken, A. R. & Dentith, M. C. 2018. The deep crustal structure of the Warakurna LIP, and insights on Proterozoic LIP processes and mineralisation. Gondwana Research 56, 1–11.

Bahr, K., Boutilier, R. & Mononen, T. 2023. Machine learning topic detection of social media attitudes about mineral development in Europe. In: Nykänen, V., Cook, N. & Kaija, J. (eds) EU SuperCluster Lapland Geoconference – October 30-31, 2023, Hotel Santa Claus, Rovaniemi, Finland. Geological Survey of Finland, Open File Research Report 55/2023. (this issue)

Barnes, S. J., Cruden, A. R., Arndt, N. & Saumur, B. M. 2016. The mineral system approach applied to magmatic Ni–Cu–PGE sulphide deposits. Ore Geology Reviews 76, 296316.

Boscaini, A., Marzoli, A., Bertrand, H., Chiaradia, M., Jourdan, F., Faccenda, M., Meyzen, C. M., Callegaro, S. & Durán, L. S. 2022. Cratonic keels controlled the emplacement of the Central Atlantic Magmatic Province (CAMP). Earth and Planetary Science Letters 584, p.117480.

Guo, F. F., Maier, W. D., Heinonen, J., Hanski, E., Vuollo, J., Huhma, H., O'Brein, H. & Yang, S. H. 2023. Geochemistry of the 2.44 Ga mafic dykes in Northern Finland: implication for platinium group elements mineralization. Lithos. (in press)

Kalubowila, C., Dujmović, L., Pospiech, S. & Sarala, P. 2023. CoDA based approach to surficial and till geochemistry. In: Nykänen, V., Cook, N. & Kaija, J. (eds) EU SuperCluster Lapland Geoconference – October 30-31, 2023, Hotel Santa Claus, Rovaniemi, Finland. Geological Survey of Finland, Open File Research Report 55/2023. (this issue)

Porwal, A., Das, R. D., Chaudhary, B., Gonzalez-Alvarez, I. & Kreuzer, O. 2015. Fuzzy inference systems for prospectivity modeling of mineral systems and a case-study for prospectivity mapping of surficial Uranium in Yeelirrie Area, Western Australia. Ore Geology Reviews 71, 839–852.

REUSING SECONDARY MINERAL RESOURCES FOR THE ENERGY TRANSITION: THE PROJECT START EXAMPLE

by

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In an era characterised by environmental challenges and growing awareness of the finite nature of fossil fuels, the need for a global shift from traditional energy sources to clean and sustainable alternatives have never been more urgent. The shift towards these alternatives not only curtails carbon emissions but also reduces air and water pollution, leading to improved public health and a revitalised environment. Additionally, this shift has a wide-ranging impact on various aspects of society, the environment, and global economies, namely: a) Environmental Impact (Climate Change Mitigation, Air Quality Improvement), b) Energy Security (Reduced Dependence on Imports), c) Economic Impacts (Job Creation, New industries, Diversification), d) Technological Innovation (Research and Development, Technological Breakthroughs), e) Global Relations and Diplomacy (Reduced Geopolitical Tensions, Increased Collaborative Efforts), f) Energy Access and

Equity, g) Infrastructure and Urban Development (Decentralisation, Sustainable Cities), h) Natural Resource (land/water) Preservation, i) Long-Term Sustainability (Extended Resource availability and Environmental legacy) and j) Carbon emission reduction and policy incentives. All focused in the ambitious objectives of the EU's Green Deal in 2019 and the EU Action Plan on Critical Raw Materials in 2020.

The project START (Sustainable Energy Harvesting Systems Based on Innovative Mine Waste Recycling, Horizon Europe Grant Agreement ID: 101058632, www.start-heproject.com) is contributing to these objectives by researching the feasibility of using secondary resources from mine dumps and tailings. The final goal is to build an innovation ecosystem in the EU related to the development of sustainable tellurium-free thermoelectric (TE) devices with the highest economic efficiency, suitable to be applied in waste heat recovery systems, such as the heat rejected from industrial processes, and in other applications including wearables. The START project is formed by a consortium of 15 entities from 11 European countries, has a duration of 4 years and a co-funded budget of around 9.2 M€ (Fig. 1).

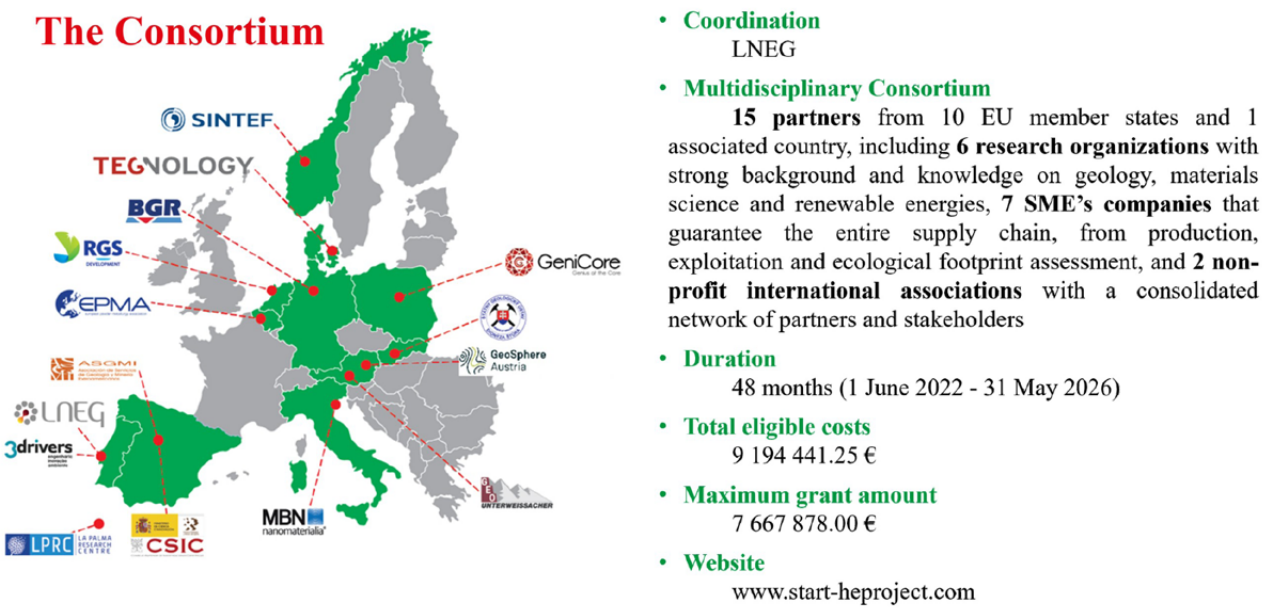

Fig. 1. START project key facts.

PROJECT SCOPE

Current commercial thermoelectric devices incorporate p-type semiconductor materials that are produced from expensive and rare elements, namely tellurium, which is toxic and predominantly sourced in China. As an alternative approach for the replacement of the tellurium-based p-type semiconductor materials, START proposes a unique technological solution and value-chain based on a "waste material-waste heat to power" methodology. This approach implies the production of sulphide p-type semiconductor materials that will incorporate, amongst others, discarded mining waste sulphides, mainly consisting of the tetrahedrite-tennantite mineral series. Thus, the project concept also includes the stages of material processing, device design and production, testing and validation (Fig. 2). The aim is to produce a TE device reaching TRL6, with the START TE device demonstrated in industrial processes. As a first step, several historical European mining sites have

been targeted for collection of tetrahedrite-tennantite minerals, namely: a) Austria: Leogang (Nöckelberg, Barbarastollen) and Schwaz (Sandpocher, Antonihalde, Sigmundhalde), b), Germany: Rammelsberg mine, Bergwerkswohlfahrt mine, c) Portugal: Neves Corvo, Barrigão and Brancanes mines, d) Slovakia: Rožňava mine, e) Spain: La Sierrecilla, El Corriellu, Peña Negra, Torres de Albarracín, Lanteira mines, amongst others. The collected minerals are undergoing processing and will feed the material processing in the upcoming stages.

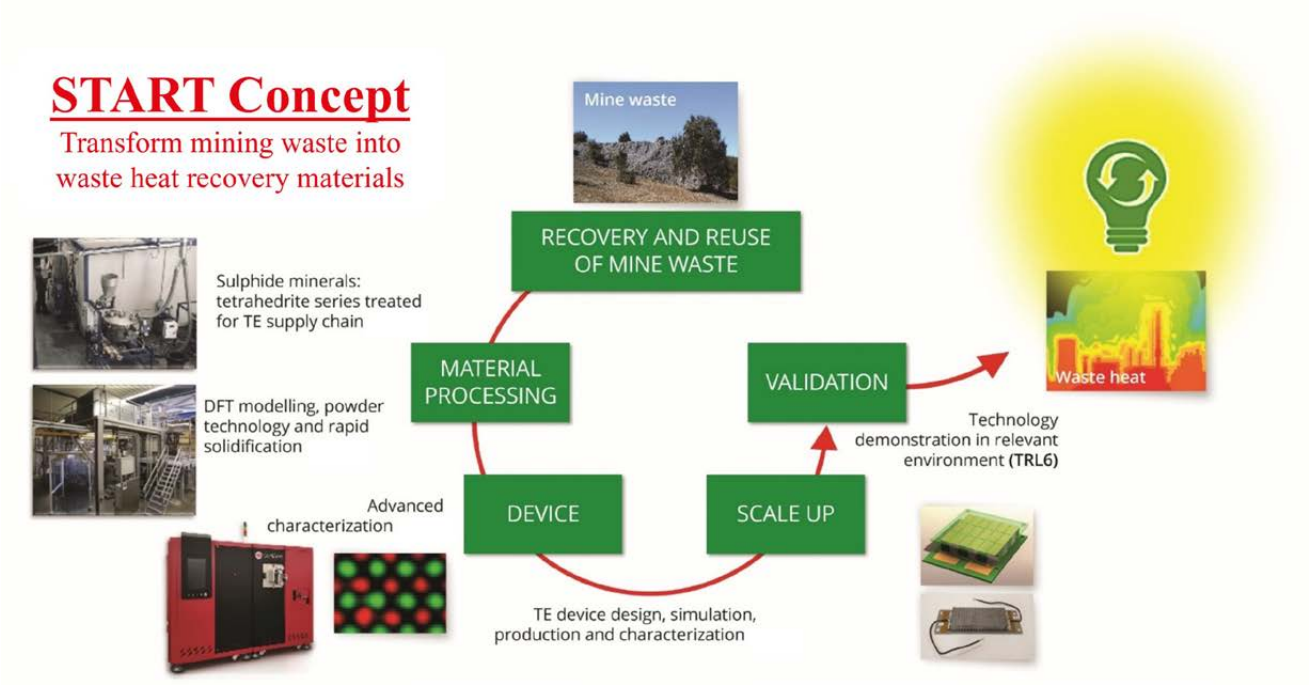

Fig. 2. Project concept with description of the main activities being implemented.

Fig. 3. Some of the environment and locations where samples were collected for the START project.

PROJECT IMPACT

The START project proposes the use and transformation of the tetrahedrite-tennantite mineral series into thermoelectric materials for waste heat recovery. This represents an opportunity for an efficient use of the EU's discarded secondary resources, reducing its waste and dependency on third countries and offers a competitive solution for the development of renewable energy ecosystems in a sustainable manner using thermoelectric systems. Thus, START expected impacts are as follows:

- Development of a resilient and sustainable critical raw materials supply chain for thermoelectric-based renewable energy ecosystems.
- The incorporation of p-type thermoelectric materials produced from tetrahedrite-tennantite minerals collected in mine wastes, which is an earth-abundant mineral and available in European mine wastes, offers a simple and economically competitive solution and increase the EU raw materials supply capability and added value. Recycling and usage of mine wastes, more specifically of the tetrahedrite-tennantite mineral series that presently have no useful use and have low economic value, to produce new products will positively influence the resilience of the EU raw materials supply capability by reducing the EU dependency on raw material imports from third countries.
- Creation of new market opportunities for mineral raw materials sustainably produced in the EU. The conversion of secondary mineral resources, collected in European mine wastes, into useful and value-added products will create new market opportunities.
- Environmental impact. Reprocessing of sulphide-containing mining residues, will act as remediation of potential acid mine drainage. Additionally, the use of energy harvesting systems offers a contribution to the reduction of fossil fuels consumption with a great impact on the increase of the overall efficiency of energy production and consumption systems, as well as on the reduction of the greenhouse gas emissions.
- Innovative value chain. START will create an innovative value chain linking secure European mineral resources and renewable energy harvesting production. The mining industry, which is increasingly aware of its environmental footprint, as well as the materials and energy harvesting system producers, which rely on more abundant materials while maintaining high performance, will benefit strongly from the project outcomes.
- Create new circular business models with a convincing and quantified socio-economic impact. START will establish a new rapid growth commercial ecosystem that will attract new stakeholders exploiting market opportunities for replication and market development and an opportunity for European SMEs to join in. The START commercial ecosystem will be maintained through the creation of a new business entity, the START Service Company.

CONTRIBUTION TO CRITICAL RAW MATERIALS ACTION PLAN

The START project contributes to the implementation of the following actions of the EU Action Plan on Critical Raw Materials:

Action 3 – Launch research and innovation on waste processing, advanced materials and substitution of critical raw materials.

Action 4 – Map the potential supply of secondary critical raw materials in Europe and identify viable recovery projects.
Action 5 – Identify priority mining and processing projects for critical raw materials in the EU.
Action 8 – Develop research and innovation projects to reduce environmental impacts of raw materials extraction and processing.
Action 9 – Develop strategic international partnerships to secure a diversified supply of sustainable critical raw materials, starting with pilot partnerships with Canada, interested countries in Africa and the EU's neighbourhood. (partially)

CONTRIBUTION TO THE UN SUSTAINABLE DEVELOPMENT GOALS

START also contributes to the following UN Sustainable Development Goals, namely:

Goal 7 – Affordable and clean energy
Goal 9 – Industry, Innovation, and infrastructure
Goal 11 – Sustainable cities and communities

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TRIDENT: TECHNOLOGY-BASED IMPACT ASSESSMENT TOOL FOR SUSTAINABLE, TRANSPARENT DEEP SEA MINING EXPLORATION AND EXPLOITATION

by

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The quest for raw materials within an environmentally adequate framework, especially in defying conditions, requires the development of technological breakthroughs. TRIDENT addresses this goal entirely, by creating a dependable, transparent, and cost-effective system for forecasting and ongoing environmental impact monitoring of exploration and exploitation activities in the deep-sea, paving the way for comprehensive monitoring of the exploitation of seabed mineral resources. These new tools will empower a shared responsibility to supervise and monitor deep-sea activities, and simultaneously preserve and enhance marine habitats, supporting an environmentally sustainable blue economy. Among others, the system will allow the assessment of the state of mining operations, the state of ecosystems, and provide forecasts of their short and long-term changes. Complementary TRIDENT will foster the development of mitigation strategies for the negative impacts, or an emergency response to severe events such raw materials' leaks in the water column.

Potential environmental consequences and mitigation strategies must be fully understood before mining activities may be considered. The created effective monitoring and inspection system will conform to international and national legal frameworks. Environmental sustainability and complete transparency in deep-sea exploitation governance are critical considerations for widespread approval.

TRIDENT will create, develop and integrate innovative solutions and technology ensuring autonomous operation in remote areas, under extreme conditions, while providing real-time data to authorities responsible for permits and supervision. TRIDENT's efficient monitoring and inspection system will abide by national and international legal frameworks. Be it at the sea surface, mid-water, and bottom, TRIDENT will identify all significant physical, chemical, geological, and biological characteristics that must be monitored, while also looking for data gaps and suggest procedures for addressing them.

These are fundamental steps in the process of obtaining statistically consistent environmental baselines, launch reliable indicators of good environmental status and establish thresholds for significant impact, enabling the standardisation of tools and methods. TRIDENT will consequently develop and test an innovative and dynamic integrated system, gathering mobile and stationary observatory platforms equipped with state-of-the-art automatic sensors and samplers to measure environmental parameters using a (deep-sea) mining simulation and reference areas at representative spatial and temporal scales. This team of relocatable and mobile observatories with autonomous operations, combined with adaptive observation strategies will be critical for a cost-effective monitoring solution with optimal spatiotemporal coverage of the monitoring areas. To communicate the gathered

data in near real-time and support quick actions for preventing serious harm to the environment, the system will incorporate high-capacity data processing pipelines able to gather, transmit, process, and display the monitoring data. All the data will be INSPIRE compliant and made available through the European Marine Observation and Data Network (EMODnet). Finally, the information and the technology set in place by TRIDENT will grant systemic and technological solutions that will allow the prediction of probable impacts that result from the use of the developed monitoring and mitigations techniques.

TRIDENT embraces the concept of proactive collaboration with researchers, scientists, governmental organisations, industry, policymakers, and organisations involved in sea governance to collaboratively develop an integrated impact assessment system solution, practices, standards, conventions, guidelines, and recommendations for required legal instruments, resulting in economically viable, environmentally sound, and socially acceptable exploration and extraction of the World and the EU's deep-sea and sub-sea floor resources aligned with European maritime and environment related policies and strategies. The ISA (International Seabed Authority) has been developing recommendations for assessing potential environmental consequences and acquiring baseline data, which TRIDENT will strive to incorporate as much as possible into its schedule of activities and data acquisition. TRIDENT's current relationships with the ISA and national regulators will enable close cooperation and conversation with deep-sea mining regulators.

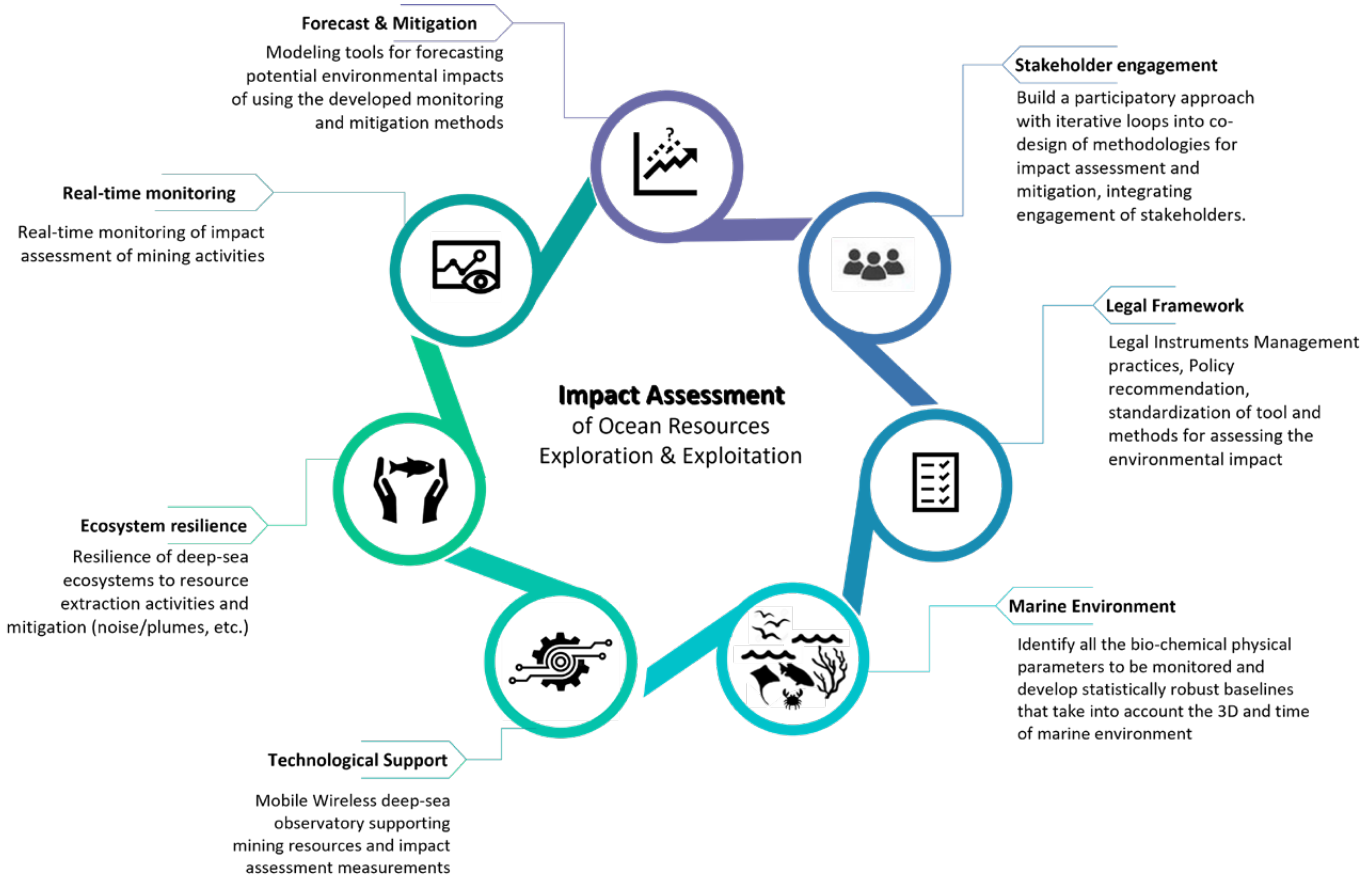

Fig. 1. Holistic approach of Impact Assessment of Ocean Resources Exploration and Exploitation.

TRIDENT OBJECTIVES

TRIDENT has seven objectives that will constitute the core aggregator of all developments that will be performed in the project. The overall aim is that TRIDENT activities will be interconnected providing an overall view of how to perform an impact assessment, forecasts and mitigation through technological, environmental and legal solutions using a clear and decisive stakeholder co-design, co-development and co-implementation approach. The on site deep-sea mining simulation is intended to address the largest possible set of variables in terms of actions and potential impacts in this oceanic context, one that is in need of guidelines and regulations developed upon a solid scientific research work. Therefore, the following objectives are listed having this scenario as the basis for all the work to be developed in the TRIDENT project:

Objective 1 – To develop an integral environmental impact assessment (EIA) capability.

Objective 2 – To advance the understanding of geological, biological and environmental processes (associated with deep-sea raw materials exploitation).

Objective 3 – To develop an innovative dynamic infrastructure for real-time positioning, navigation, communication and awareness of mining and monitoring systems.

Objective 4 – To develop an innovative mobile autonomous high-tech laboratory transferred into the field (deep-sea, water column and surface) attached or stand-alone and easily transported.

Objective 5 – To develop a holistic governance framework for Europe's Ocean resources sustainable exploitation.

Objective 6 – Final Demonstration in a representative environment.

Objective 7 – Lead the creation of a new commercial ecosystem driven by a cluster of European service and technology providers, satisfying client requirements globally.

AMBITION AND BEYOND STATE OF-THE ART

The increase of global demand on raw materials needed for the population growth and energy transition will be the driver to DSM, although we need to develop solutions to monitor and stewardship these types of activities. TRIDENT's ambition is to promote an innovation breakthrough in deep-sea environmental impact assessment by identifying mitigation solutions, developing new methodologies and operational techniques, contributing to a robust legal framework, collaborating strongly with ISA, and allowing the access to sea world mineral reserves in a safe, environmentally friendly, industrially viable and socially accepted way.

Presently the technological developments available for deep-sea deployment, in addition to the lack of the reliability and robustness, are limited by the depth requirement, the level of autonomy, the computer power processing, the endurance, and the lack of reliable underwater communications capacity.

TRIDENT proposes to progress beyond the current state-of-art by filling the described technological limitations and gaps and establishing advanced methodologies for real-time monitoring of environmental impacts and providing mitigation measures in the context of deep-sea mining (polymetallic sulphides, crusts and nodules). TRIDENT will provide a wireless fixed and mobile (modular) network of sensors and autonomous robots providing real-time environmental monitoring and data transfer from the deep remote ocean to shore, validated in relevant scenarios.

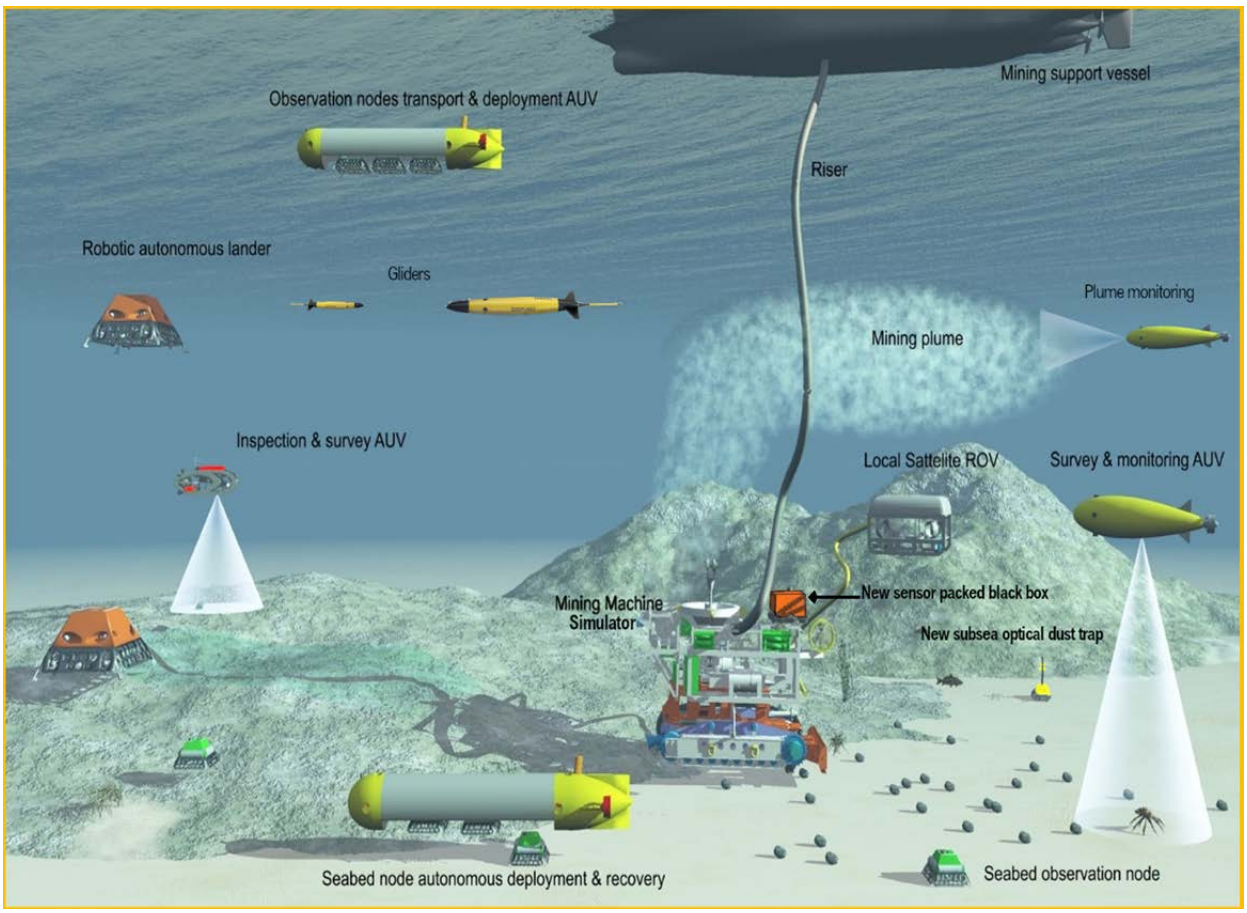

Fig. 2. Artist's rendition of TRIDENT's *in-situ* test.

AGEMERA PROJECT STUDIES LOCAL PEOPLE'S PERCEPTIONS: IS THE MINERAL INDUSTRY SUPPORTING THE FUTURE OF LOCAL COMMUNITIES?

by

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Recognising and respecting local people's opinions on mineral exploration and mining are a necessity for the mineral industry. Failing to do so damages a company's reputation and the local acceptance of a project. This may seriously harm not just the individual project, but the legitimacy of the entire industry. Bad news spreads quickly in this globalised world, especially via social media (Ernst & Young 2020, 2022, Suopajärvi et al. 2022).

One important task in AGEMERA (2023) WP2 is to study local people's perceptions of mineral exploration and mining. For this purpose, the University of Lapland with its WP2 partners designed a questionnaire concerning the social impacts and acceptance of mineral exploration and mining, and the mineral industry's role in developing sustainable communities.

The survey was piloted in Northern Finland between 3 February and 3 March 2023. The data were collected through an online survey published on the website of the University of Lapland and promoted on several local Facebook forums. The survey targeted the residents of Kuusamo, Posio, and Rovaniemi municipalities, as these are potential target areas of AGEMERA field studies (Table 1).

We received 293 responses, mostly from residents of Kuusamo and Rovaniemi. The mean age of the sample was 52 years and most respondents were men. Most had higher education and were employed. They came from various employment sectors with no significant preponderance in any one sector. The vast majority of the respondents had lived in the aforementioned municipalities for over 10 years and most were planning to stay in their home municipalities in the long term.

Table 1. Municipality of residence.

Total (*n*)	Kuusamo	Posio	Rovaniemi	Outside the research area	Did not respond
293	116	13	107	46	11

For the analysis presented in this abstract, only respondents living permanently in Kuusamo, Posio, or Rovaniemi were included.

In the analyses, social license to operate (SLO) refers to the local acceptance of mines in the respondents' home region. People could respond to the statement "I approve of mining in my home region" using a five-point Likert scale in which 1 = completely disagree, 2 = somewhat disagree, 3 = neither agree nor disagree, 4 = somewhat agree, and 5 = completely agree. In this presentation, the response option "I don't know" has been omitted from the analysis. The responses were interpreted as follows: 1 = resistance, 2 = refusal, 3 = no clear opinion, 4 = acceptance, and 5 = support.

Those who decided to complete the questionnaire clearly had an opinion on mining, and fewer than 4% of the respondents had no clear opinion. Of the respondents, half were critical of mining in their home area and almost half (46%) were pro-mining. The views of male respondents were equally divided for and against, whereas females were slightly more critical, with 51% opposing and 43% supporting mining. In this case, therefore, gender did not explain the acceptance/non-acceptance of mining as opinions were divided among both women and men. When comparing acceptance with level of education, people with higher education seemed to be more pro-mining, as 56% of them accepted or supported mining.

As often repeated in the academic literature, local acceptance of mining is context specific. In this survey, 61% of respondents living in the Kuusamo–Posio area did not accept mining in their home area, whereas only 38% of respondents from Rovaniemi rejected mining. The reason for this difference may be that information about the survey reached different kinds of people in different regions. As well, Kuusamo already has organised resistance to mining, namely, the Pro Kuusamo association, which is celebrating its tenth anniversary in 2023 (Pro Kuusamo 2023). Also, a clear majority of local decision-makers at the municipal level have opposed mining (e.g., Iltalehti 2021).

Accordingly, 92% of respondents who did not accept mining disagreed with the statement "Large-scale mining projects are necessary for the vitality of my home region", whereas 70% of those who accepted mining agreed with the statement. More than half of those who accepted mining (category 4 in the five-point Likert scale) did not see large-scale mining as a necessity for the locality. Hence, those who approved of mining also had critical views of the industry.

As SLO refers to present-day acceptance, we included questions about respondents' perceptions of the future of the locality and what role mining might play in it. At the moment, there is no operating mine in the research area, but mineral exploration is intensive there (Finnish Safety and Chemicals Agency 2023). A mining project developed by Suhanko Arctic Platinum Oy is ongoing on the southern border of Rovaniemi, where the company is expecting to start production in 2026 (Suhanko Arctic Platinum Oy 2023).

Respondents were asked: 1) When you think about the year 2050, what do you consider the biggest threats to your home region? 2) What is the best that can happen to your home region by 2050? The rationale behind these questions was to understand how mining is seen as part of the local future and local sustainability. As often repeated in the academic discussions, "sustainable development" is difficult to define, even being seen as an oxymoron, and the definition depends on each actor's own point of view (see, e.g., Lempinen 2019, McDonagh et al. 2020). To accommodate this, the questions were open-ended, and in fact, different respondents used different concepts of "sustainability" or "sustainable" in different contexts.

Those who opposed mining were mainly concerned about the environment. Pollution and the destruction of nature were seen as the biggest threats, and these

factors were usually associated with potential mining. However, environmental concern was not limited to these specific issues. Climate change was also viewed as a shared threat, as many of those who accepted mining were concerned about its impacts as well. Supporters of mines did not discuss environmental hazards, but instead the economic decline of the home region.

Sustainability, or more precisely its conceptual predecessor sustainable development, has been analytically divided into three pillars – environmental, economic, and social sustainability – ever since the Brundtland Commission introduced the concept to a broad audience (WCED 1987). According to our empirical data, these pillars are often inseparable from one another, and two aspects of sustainability were often intertwined in participants' responses. For example, "clean and vital nature" was seen as the most valuable asset for tourism, specifically, what is called "nature-based tourism". In the mining supporters' responses, economic development was often equated with industrial development and mining, as a necessity for population growth and demographic rejuvenation.

The vision of opportunity, hope, and positive development for the home area in 2050 was clear: a diverse economic structure, no matter one's opinion on mines. However, perceptions of how economic diversity should be built varied between the opponents and supporters of mining. People who did not want mines in their home region promoted a combination of nature-based tourism and the harvesting and refining of natural products, including the small-scale wood-processing industry. Those who supported mining development argued that, alongside tourism, there should also be other sectors for livelihoods, i.e., mining and industry in general. What worried the respondents most of all was dependency on only one sector for livelihoods, making living in the home area more vulnerable to global economic fluctuations.

To understand SLO in mineral exploration and mining, "local context is the key" as Jason Prno (2013) has argued. But what exactly are the factors that affect acceptance? The answer can be found, for example, by a comparative study. That is why the survey will be administered in 2023–2024 in the AGEMERA partners' research areas in different countries. How do local conditions and the operating practices of different companies, for example, affect the acceptability of the mineral industry, locally as well as in society more generally? Also, it is particularly important to know how the mineral industry can support and strengthen the future of local communities.

REFERENCES

AGEMERA 2023. Building a resilient Europe through responsible mineral exploration. Available at: https://agemera.eu/. [Accessed 24.8.2023]

Ernst & Young 2020. Top 10 business risks and opportunities – 2020. Available at: https://www.ey.com/en_es/mining-metals/10-business-risks-facing-mining-and-metals. [Accessed 23.8.2023]

Ernst & Young 2022. Top 10 business risks and opportunities for mining and metals in 2023. Available at: https://www.ey.com/en_fi/mining-metals/risks-opportunities. [Accessed 23.8.2023]

Finnish Safety and Chemicals Agency 2023. Mining register and map service (GTK: Mineral deposits and exploration). Available at: https://gtkdata.gtk.fi/mdae/index.html. [Accessed 23.8.2023]

Iltalehti 2021. Kuusamoon puuhataan kobolttikaivosta, jota kaupunkilaiset eivät halua – taustalla vuosien taistelu. [A cobalt mine is being planned in Kuusamo, which the townspeople don't want – years of struggle in the background]. (in Finnish). Available at: https://www.iltalehti.fi/kotimaa/a/3a0848b6-967d-4489-860b-f5a5076c8eb5. [Accessed 24.8.2023]

Lempinen, H. 2019. Arctic energy and social sustainability. Palgrave Macmillan.

McDonagh, J., Ólafsdóttir, R., Weir, L., Mahon, M., Farrell M. & Conway, T. 2020. "Nothing is sustainable the way it is" – reflections on local sustainability perceptions and interpretations. In: McDonagh, J. & Tuulentie, S. (eds) Sharing knowledge for land use management: Decision-making and expertise in Europe's Northern Periphery. Edward Elgar Publishing, 100–115.

Prno, J. 2013. An analysis of factors leading to establishment of a social license to operate in the mining industry. Resour. Pol. 38, 577–590.

Pro Kuusamo 2023. Yhdistys [The Association]. (in Finnish). Available at: https://prokuusamo.fi/yhdistys/. [Accessed 24.8.2023]

Suhanko Arctic Platinum Oy 2023. Timeline of the project. Available at: https://www.suhanko.com/english. [Accessed 23.8.2023]

Suopajärvi, L., Beland Lindahl, K., Eerola, T. & Poelzer, G. 2023. Social aspects of business risk in the mineral industry: Political, reputational, and local acceptability risks facing mineral exploration. Min. Econ. 36, 321–331.

WCED 1987. Our common future. United Nations World Commission on Environment and Development. Available at: https://sustainabledevelopment.un.org/content/documents/5987our-common-future.pdf. [Accessed 23.8.2023]

DATA AVAILABILITY IN THE IMPLEMENTATION OF UNFC AND UNRMS: A VECTOR CASE STUDY, ABERDEENSHIRE, UK

by

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The Critical Raw Materials Act sets out a minimum objective to domestically extract at least 10% of the EU's annual critical raw material consumption. To achieve this, a significant increase in the number of active projects within the EU mining sector will be required. To fulfil this demand, the Critical Raw Materials Act dictates that the assessment of project viability will utilise the United Nations Framework Classification for Resources, UNFC (UNECE 2019). The UNFC enables resource accounting by allocating scores to socio-economic, geological, and project feasibility (Fig. 1a). The scoring of a resource, project, or region using the UNFC's three axes methodology provides a consistent and easily communicable scoring system of maturity and viability.

The United Nations Resource Management System (UNRMS) provides a distinct but complementary approach to considering the development of a domestic source of critical raw materials within the EU. The UNRMS details a system for sustainable development throughout a project, considering a suite of environmental, social, and governance factors laid out in 12 principles and >50 requirements aligned to the Sustainable Development Goals (Fig. 1b) (UNECE 2021). The UNRMS can be considered at a national, regional, and project level. Despite UNFC and UNRMS both having critical roles in the implementation of the Critical Raw Materials Act and delivery of a sustainable domestic supply of critical raw materials, there are limited published case studies which illustrate implementation of either system within the mining sector (e.g. Bide 2021, CIOS LEP 2023).

VECTOR is an EU Horizon and UKRI co-funded research project assessing the technical, environmental, and social challenges to developing a domestic supply of critical raw materials within in Europe, with a focus on those most applicable to early exploration projects. Within the project, we have evaluated challenges in the implementation of UNFC and UNRMS, particularly regarding data availability. Here we present a case study, within the VECTOR GIS platform and data repository, of all relevant open access and freely available data that facilitates alignment to UNFC and UNRMS for Aberdeenshire, UK; an underexplored region with the potential to be prospective for cobalt, nickel, and graphite (UK Critical Minerals Intelligence Centre 2023). Data were collected from a variety of sources, including: the British Geological Survey, past EU research projects, environment agencies, and local government.

We find that data relevant to the scoring of all three UNFC axes were available and accessible for inclusion in the VECTOR platform. However, the majority of data that could be accessed is of a precision and accuracy that allowed scoring only in the least mature categories of each axis. This is likely the result of the data required for scoring in the most mature categories of each axis being commercially sensitive. Therefore, it is not freely and publicly available. Data relevant to 9 of the 12 of the URMS principles were available and accessible. Data linked to 'service orientation', 'value addition', and 'continues strengthening of core competencies and capabilities' were not. Where data is available, it is frequently presented in an inconsistent format, limiting the amount of data integration possible within the platform and repository.

Through this analysis, we have identified several VECTOR primary research deliverables that will produce data and methodologies that can assist with the implementation of UNFC and UNRMS across Europe in early critical raw material exploration projects. Within VECTOR, the testing of minimally disruptive exploration technologies, development of methods to assess shared value between all stakeholders (inclusive of civil society), and proposal of new business models within the sector will generate new data aligned to the three UNFC axes and many of the UNRMS principles. In addition, the development of novel data integration tools to facilitate comparison of data presented in diverse formats will help overcome issues identified in our case study, further aiding implementation of UNFC and UNRMS.

Overall, our assessment of the availability of open-access data to facilitate alignment to UNFC and UNRMS in Aberdeenshire provides one of the first applications of both frameworks to the mining sector. We have demonstrated that application of UNFC, as stipulated by the Critical Raw Materials Act, is possible using open-source data but only to score the least mature categories of projects. Data required for alignment to UNRMS is available for 9 of the 12 principles but in diverse formats, preventing the true integration of information. VECTOR project research will provide methodologies that can be used to fill some of the identified data gaps and facilitate the integration of diverse data formats.

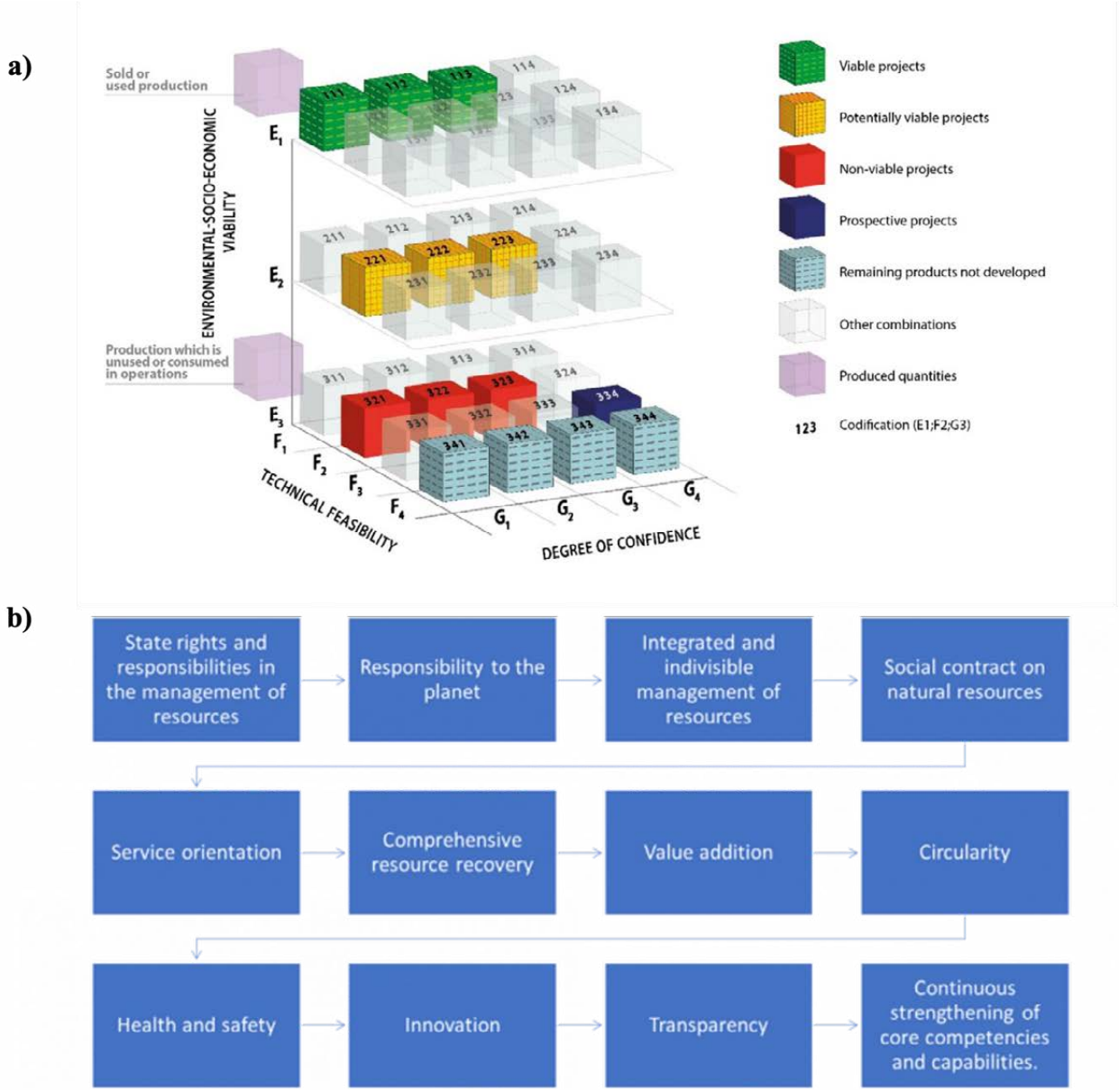

Fig. 1. Diagrams of a) UNFC scoring axes (UNECE 2019), b) 12 UNRMS principles (UNECE 2021).

REFERENCES

Bide, T. 2021. The use of UNFC by National Geological Surveys, a case study from the UK Resource Management Week 2021. Available at: https://unece.org/sites/default/files/2021-04/03_Tom_Bide_UK_UNFC_Case_study_0.pdf

CIOS LEP 2022. Cornwall and the Isles of Scilly Technology Metals Opportunity. Available at: https://cioslep.com/wp-content/uploads/2023/02/Cornwall-and-the-Isles-of-Scilly-Tech-Metals-Opportunity.pdf

UK Critical Minerals Intelligence Centre 2023. Potential for Critical Raw Material Prospectivity in the UK. Available at: https://ukcmic.org/downloads/reports/ukcmic-potential-for-critical-raw-material-prospectivity-in-the-uk-cr23024.pdf

UNECE 2019. United Nations Framework Classification for Resources Update 2019. Available at: https://unece.org/fileadmin/DAM/energy/se/pdfs/UNFC/publ/UNFC_ES61_Update_2019.pdf

UNECE 2021. United Nations Resource Management System: an overview of concepts, objectives and requirements. Available at: https://unece.org/sites/default/files/2021-05/2017886_E_ECE_ENERGY_134_WEB.pdf

GROUNDWATER MODELLING WITH LIMITED DATA AS A DECISION-MAKING TOOL

by

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Groundwater management plays a crucial role in ensuring sustainable water resources for various sectors. However, the inherent complexity of groundwater systems and the scarcity of data often present challenges for effective decision-making. This abstract explores the significance of groundwater modelling as a valuable tool in decision-making processes, particularly in situations where data availability is limited. The abstract delves into the methodologies and approaches used to develop groundwater models with sparse data. It discusses the benefits and limitations of such models in aiding decision-making across areas like water allocation, environmental impact assessment, contamination remediation, mine planning. Through case studies and examples, this abstract highlights instances where groundwater modelling with limited data has informed critical decisions and influenced resource management strategies. By showcasing the potential of these models, this abstract contributes to a better understanding of how they can enhance sustainable groundwater management even in data-constrained environments.

Keywords: groundwater modelling, sensitivity analyses, optimisation, mine inflow rates

INTRODUCTION

Groundwater modelling is a powerful tool for decision-making in water resources management. However, the availability of data is often limited, making it challenging to build accurate models. This study presents the results of a preliminary groundwater model built for an area with limited data using sensitivity analyses. The model was built using FEFLOW (Diersch 2005) and calibrated using groundwater head levels data from a limited number of observation wells. The sensitivity analyses were conducted to evaluate the impact of key parameters on the model results. The preliminary model was then used to simulate different scenarios to evaluate the impact of groundwater pumping and dewatering on the groundwater table (groundwater levels) in area. The results showed that the groundwater model could be a useful tool for decision-making in the absence of comprehensive data. However, further data collection and model refinements might be necessary to

improve the model's accuracy and reliability. Overall, this study highlights the importance of sensitivity analyses in groundwater modelling to identify critical parameters and uncertainties in the model's outputs.

METHODOLOGY

Case Study Area

The case study focuses on a mine development site located in northern Sweden, where detailed investigations were carried out to determine the hydraulic properties of lithological units through drilling and aquifer tests conducted in boreholes and observation wells. These investigations aimed to uncover the hydrostratigraphic units in the study area, providing essential information for the site's development.

The study area encompasses two significant surface water bodies; the primary river that drains the basin where the mine site is located in, and a secondary creek that meanders towards the main river, passing in close proximity to the mine site (See Fig. 1).

Based on the preliminary hydrogeological characterisation studies conducted in the case study area, the groundwater level is seemed shallow and discharges to surface water bodies through creek beds or wetlands in the area. The hydrogeological characterisation of the area indicates two (2) different hydrostratigraphical units exists below the soil groups and overburden in the area. From shallow to deep, the first unit is moraine with its hydraulic conductivity is 1E-7 m/s and the second unit is bedrock (intrusive) with its hydraulic conductivity in top of formation is in range between 1E-6 m/s to 1E-7 m/s, and has a descending conductivity value with depth. These 2 units have direct relation with the ore body which the mining plan is being developed. A conceptual representation of the study area can be found in Figure 1.

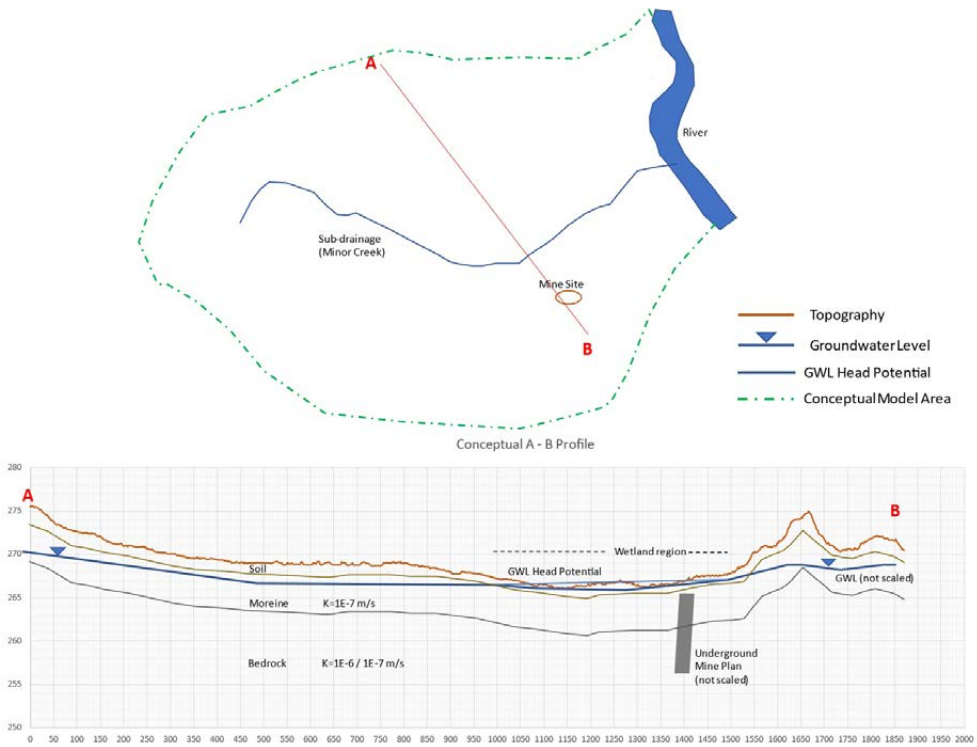

Fig. 1. Conceptual Hydrogeological Settings of the Study Area.

Numerical Modelling Approach

Appropriate boundary conditions that can best represent the dynamics of groundwater and surface water in accordance with the conceptual model established for the site were assigned in the FEFLOW software (Diersch 2005), which was preferred for the numerical model setup.

In order to build a numerical model that is closest to the real system, boundary conditions are determined in accordance with the conceptual model by using limited data obtained from the study area and characteristic background data of the region (topography, meteorological data, satellite images, etc.) and transferred to the modelling environment.

The main river, which is conceptually considered to have a direct relationship with groundwater, the sub-drainage creek towards to this river, and lakes with varying sizes are assigned as a first order boundary condition (Dirichlet BC) within the model domain. Only the Seepage Faces boundary condition (constrained 1st order boundary condition) is applied for the sub-drainage creek in regards with the conceptual approach that the groundwater discharges through the creek beds. The watershed boundaries, which also form the conceptual model boundaries and coincide with groundwater divide, are assigned to the numerical model as a no-flow boundary condition. A conceptual representation of the boundary conditions defined in the model is shown in Figure 2.

The hydrostratigraphic units identified in the study area are assumed to be homogeneous and isotropic, and the hydraulic conductivities obtained from aquifer tests carried out in observation wells drilled in these units are reflected in the model with their geometric averages, taking into account the depths of the tests and logarithmic distribution of hydraulic conductivities.

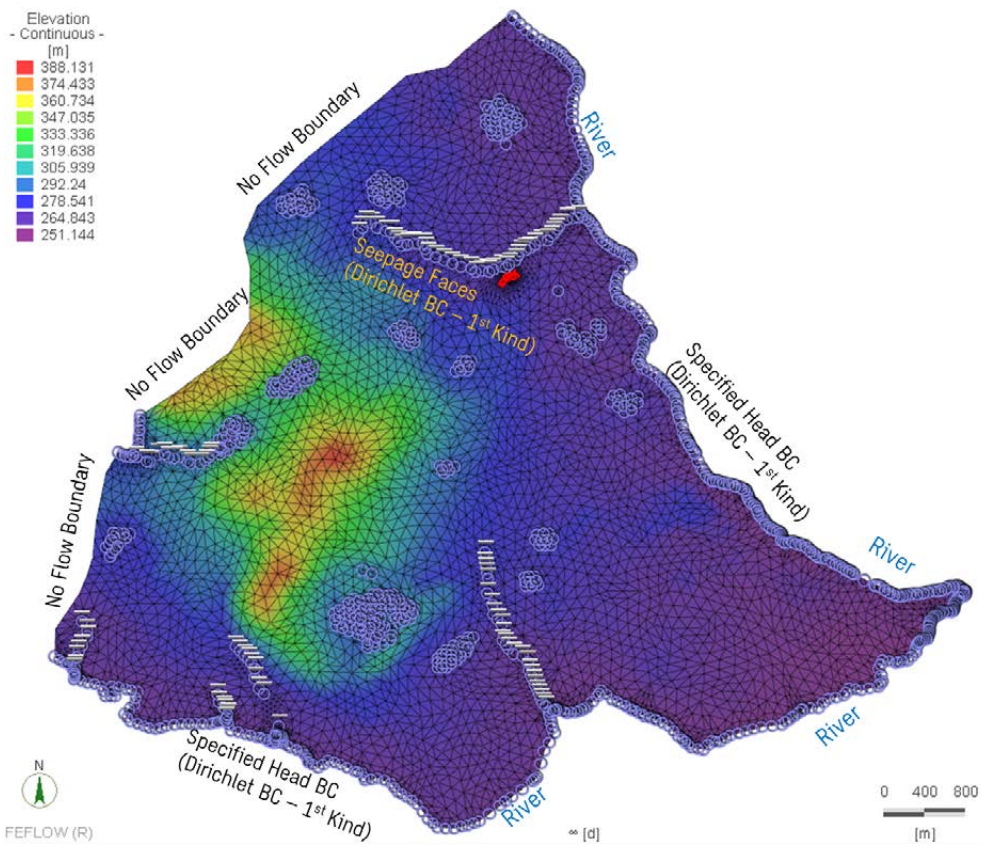

Fig. 2. Boundary Conditions in Numerical Modelling Setup.

A hydrological water budget for the study area has been worked out considering best representative meteorological data provided by Swedish Meteorological and Hydrological Institute (SMHI). A literature review was also carried out to obtain a representative groundwater recharge for the region. As a result of all the studies, 110mm/year groundwater recharge was accepted as the initial input to the numerical model.

Calibration

The calibration process in groundwater modelling ensures that the model accurately reflects the complex and dynamic nature of the subsurface system, allowing for reliable predictions and informed decision-making. The model was calibrated according to the groundwater head levels. As a result of the calibration, it is seen that the model was converged to the real system with a Normalised Root Mean Square Error (NRMSE) of approximately 0.12. A total of 47 observation points were used in the calibration of the model.

Sensitivity Analyses

Conducting sensitivity analyses in groundwater modelling is essential for identifying the key parameters that significantly impact the model output, ensuring accurate and reliable predictions.

For sensitivity analysis, groundwater recharge and hydraulic conductivity parameters of hydrostratigraphic units, which are thought to affect the model results the most, were considered. A total of 8 scenarios, including the base case scenario, were run for each parameter. Information about these scenarios is given in Table1.

Table 1. Scenarios for Sensitivity Analyses.

Scenarios	Parameter-1	Parameter-1 Value	Parameter-2	Parameter-2 Value	Result-1	Result-2
Base Case	Ground-water Recharge (mm/year)	110	–	–	RMSE	Mine Inflow Rate (m3/day) (Steady State – With Mine Plan)
Recharge1		90				
Recharge2		100				
Recharge3		120				
Recharge4		130				
Base Case	Bedrock Hydraulic Conductivity (K) (m/s)	1E-6 / 1E-7	Moraine Hydraulic Conductivity (K) (m/s)	1E-7	RMSE	Mine Inflow Rate (m3/day) (Steady State – With Mine Plan)
Conductivity1		1E-7		1E-7		
Conductivity2		1E-8		1E-7		
Conductivity3		1E-6		1E-7		
Conductivity4		1E-7		1E-6		
Conductivity5		1E-8		1E-6		
Conductivity6		1E-6		1E-6		
Conductivity7		1E-7		1E-8		
Conductivity8		1E-8		1E-8		

RESULTS

The results of the sensitivity analyses are summarised in Table 2.

Table 2. Results of Sensitivity Analyses, R – recharge, K – hydraulic conductivity (1 – bedrock, 2 – moraine), inflow rates for mine development levels from 1 to 8 including total inflow indicated.

Scenarios	R, mm/yr	RMSE	Mine Inflow Rates (m3/day)								
			1	2	3	4	5	6	7	8	Total
Base Case	110	10.78	0	0	0	16	243	344	420	1125	2148
Recharge1	90	11.86	0	0	0	10	183	327	411	1121	2051
Recharge2	100	11.07	0	0	0	12	212	333	415	1122	2094
Recharge3	120	11.20	0	0	0	24	251	350	422	1134	2181
Recharge4	130	12.28	0	0	0	19	251	355	424	1137	2185

Scenarios	K1, m/s	K2, m/s	RMSE	Mine Inflow Rates (m3/day)								
				1	2	3	4	5	6	7	8	Total
Base Case	1E-6/7	1E-7	10.78	0	0	0	16	243	344	420	1125	2148
Conductivity1	1E-7	1E-7	10.82	0	0	5	31	74	97	100	224	532
Conductivity2	1E-8	1E-7	68.99	20	12	12	12	11	11	11	24	114
Conductivity3	1E-6	1E-7	27.47	0	0	0	0	217	582	790	1988	3576
Conductivity4	1E-7	1E-6	13.88	0	0	47	85	100	96	106	237	671
Conductivity5	1E-8	1E-6	13.19	20	12	12	12	11	11	11	24	114
Conductivity6	1E-6	1E-6	28.12	0	0	0	0	247	598	798	2017	3660
Conductivity7	1E-7	1E-8	11.46	0	0	13	23	72	88	72	167	434
Conductivity8	1E-8	1E-8	33.15	0	0	13	23	72	88	72	167	434

CONCLUSIONS

The sensitivity results show that; compared to the groundwater recharge, the modelled mine inflow rates are more sensitive to the changing hydraulic conductivity properties of the hydrostratigraphic units associated with the ore zone in the mine planning area. Furthermore, hydraulic properties of the bedrock demonstrate larger importance for mine ingress compared to that of the moraine. This further suggest that a larger investigation effort is required to map hydraulic properties of the bedrock in the vicinity of planned underground operation. Thus, based on the results of a more representative model after a more detailed bedrock analysis, groundwater modelling efforts will enable better assessments of the environmental impacts, better estimation of the amount of water that will flow into the mine, and therefore more comprehensive and precise water management plans. It will also be possible to make a safer mine planning together with the prediction of groundwater related situations may arise.

In conclusion, the sensitivity analysis results in groundwater modelling play a crucial role in determining the reliability and accuracy of the model. The analysis helps identify the most influential factors affecting the model's output and quantify their effects on the results. This information can be used to optimise the model and improve its predictive ability. The sensitivity analysis also provides insight into the uncertainties associated with the model, which can be used to assess the

risk associated with the model's predictions. Overall, the sensitivity analysis is an essential tool for groundwater modelling, and its results should be carefully considered in any decision-making process involving the model's output.

REFERENCES

Diersch, H.-J. G. 2005. FEFLOW Software – Finite Element Subsurface Flow and Transport Simulation System – Reference Manual. Berlin: WASY GmbH.

Swedish Meteorological and Hydrological Institute (SMHI). Available at: http://smhi.se. [Accessed 23.4.2021]

THE MADITRACE PROJECT: AN APPROACH TO CRMS TRACEABILITY AND CERTIFICATION INTO A DIGITAL PRODUCT PASSPORT

by

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Global commodity flows and regulatory frameworks pertaining to critical raw materials (CRMs) are high on the European economic and political agenda. Companies are also facing increased pressure to responsibly extract, process and source materials as initiatives such as the EU Battery regulation and the EU Directive on Corporate Sustainability Due Diligence come into force. This makes standardised certification schemes, transparent and secure traceability, and decentralised confidential data handling imperative. Horizon Europe research project MaDiTraCe (Material & Digital Traceability for CRM Certification), launched in January 2023, aims to provide tools and solutions in this particular topic.

To enlarge and integrate the portfolio of technological solutions for traceability and certification of responsible and sustainable raw materials supply chains into a Digital Product Passport (DPP which is compatible with the EU battery passport), will reinforce the reliability of CRMs tracking and enable the transparency of raw material use in complex supply chains.

For years to come, independent digital and analytical methodologies for CRMs traceability should be developed to integrate them into a generic certification scheme for responsible and sustainable CRMs throughout mineral supply chains from the mine to the manufactured and recycled products. Special attention will be paid to the complexity of mineral supply chains with points of material aggregation and transformation (processing, refining…) including circular economy (recycling), and implementation of coherent DPPs.

This scenario will make significant impacts on complex CRMs supply chains and will be defined by identifying and solving different gaps in current due diligence practices and assess manufacturing industry needs in respect to compliance with sustainability standards and regulation. For example, to integrate technological solutions into digital product passports, such as the battery passport, using a decentralised approach.

Initiatives implemented on an inter-regional basis are key to developing this new and necessary tool of CRM certification. In its case, the MaDiTraCe project, is a strong multi-stakeholder engagement process including upstream and downstream industrials from mining to manufacturing industry and large networks involved via the consortia (EIT RM) and clusters (ISMC) participating in the project. Continuous dialogue and consensus-building with this stakeholder community on

the traceability technologies and the certification system developed in the project will ensure to stay in line with industrial needs and expectations with respect to regulatory compliance. It will also facilitate uptake, implementation, and exploitation of the project outcomes.

On this regard, the project will provide a methodological digital framework and components to facilitate the integration of existing identification, assessment and tracing methods and tools into a trusted blockchain-based platform. Current methods rely on lot-based traceability documentation, from paper trail to automatic tagging and data integration/online transmission. The blockchain-enabled decentralised methodology addresses barriers of the current system, notably confidentiality, transparency/risk of fraud, costs as well as lack of standardisation. The information flow in the digital trail will be formalised in a way to be compatible with and support the implementation of DPPs as compliance and audit tool. The DPP concept is the guideline for the project's strategy of collecting and linking certified upstream information on the chain of custody of key commodities in a decentralised way.

On the other hand, exploit the potential of material fingerprinting (MFP) and artificial tagging, as independent mechanisms to support the credibility of mineral traceability procedures and claims (Fig. 1). This intrinsic information, contained in the mineral itself, constitutes a non-counterfeitable fingerprint and an independent traceability support from the information provided by the producers to the digital trail. This information will be traceable downstream but may be altered by 1) aggregation (mixing of different sources) and 2) transformation of the raw material (concentration, metallurgy, refining). But these transformations may also induce process-specific fingerprints that can be exploited for downstream traceability. MaDiTraCe will develop MFP for four key commodities (Li, Co, graphite, REEs/Nd) that are relevant to different supply chains, primarily batteries and magnets (e-mobility, windmills...).

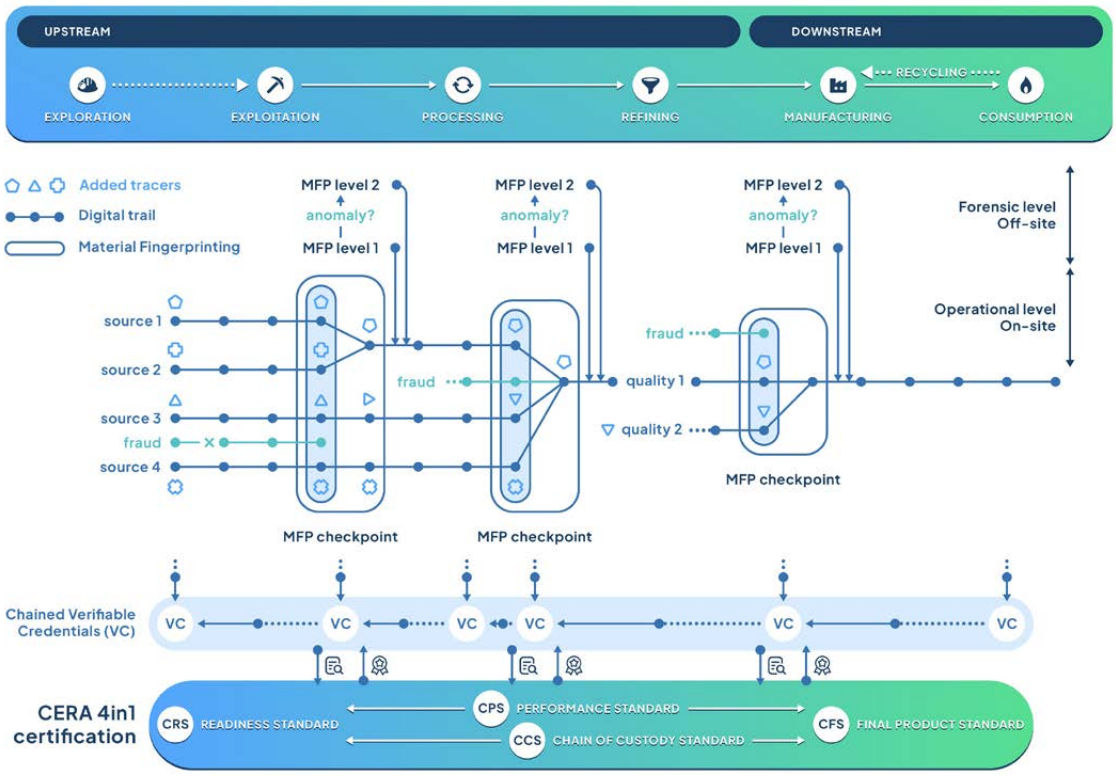

Fig. 1. Conceptual scheme of the MaDiTraCe approach to CRM traceability and certification.

MaDiTraCe will look into integrating the certification according to sustainable standards for mineral resources in DPP. MaDiTraCe will support the harmonisation of sustainability reporting standards by building on the **CERA 4in1** certification system through the addition of DPP technology (Fig. 2).

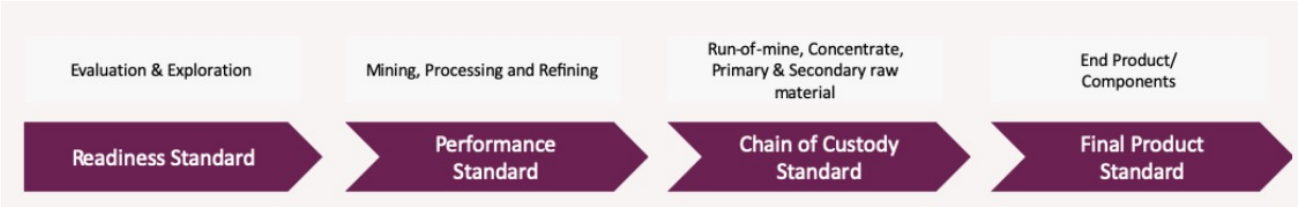

Fig. 2. The CERA 4in1 certification scheme.

The supply chain data transparency and traceability improvement through technological solutions for tracking raw material flows, will enable their sustainable sourcing and will support the EU Action Plan on CRMs.

MINING AND MINERAL EXPLORATION PROJECTS WITHIN THE NATURA 2000 AREAS IN ARCTIC FINLAND

by

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During the last decades, only three significant mineral deposits have been found in Finland: Rompas-Rajapalot (Au-Co) in Ylitornio-Rovaniemi and Sakatti (Ni-Cu-PGE-Co), and Ikkari (Au) in Sodankylä, Lapland, northern Finland (Fig. 1). None of them have been developed for a mine yet. Sakatti and Ikkari are found within the Central Lapland Greenstone Belt, and Rompas-Rajapalot within the Peräpohja Schist belt. Both areas have high potential for new discoveries.

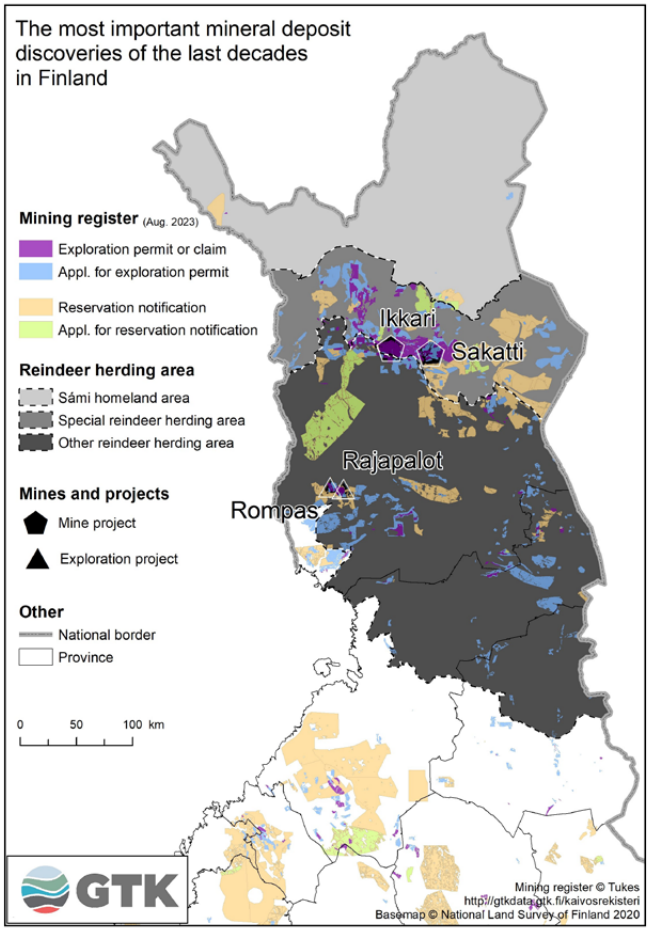

Fig. 1. Important mineral deposit discoveries of the last decades in Finland.

Here we focus on the Sakatti and Rompas-Rajapalot projects, which are partially located within Natura 2000 areas. Those are among sensitive contexts in which mining and mineral disputes emerge in Finland: nature conservation, reindeer herding, tourism destination, second homes related to water systems and association with uranium (Eerola 2022). As seen in Figure 1, both projects are also located within the reindeer herding area. In fact, they were identified by Eerola (2022) as among the Finnish mining and mineral exploration disputes (MMEDs). Table 1 summarises their characteristics. The projects are described mainly based on Eerola (2022) and their situation and strategies to adapt for the situation regarding the social license to operate (SLO) are presented. SLO means acceptance or approval of a project by a local community or more widely by society (Thomson and Boutilier 2011).

Table 1. Characteristics of the Rompas-Rajapalot and Sakatti projects and disputes related to them (after Eerola 2022). FANC = Finnish Association for Nature Conservation.

Company and its own or parent company's origin	Project/locality, activities and commodities	Issue(s)/ concerns	Indicator(s)	Main contentious actor(s)
Mawson OY/ Mawson Gold Ltd, Canadian	Rompas-Rajapalot/ Ylitornio, Rovaniemi mineral exploration: gold, cobalt (uranium)	Natura 2000 area, uranium	Beland Lindahl et al. (2023), appeals, court rulings	FANC, environmental authorities
Sakatti Mining Oy/ Anglo American plc British	Sakatti/ Sodankylä, mine project: nickel, copper	Natura 2000 area, reindeer herding	Lassila (2020), organised movement, social media group	FANC, Viiankiaapa movement, reindeer herders

The Rompas uranium deposit was discovered by the French Areva nuclear company in 2008. The property was sold to Canadian company Mawson Resources Ltd in 2010, which also found gold. Mawson found another deposit (gold and cobalt) in Rajapalot, ten kilometers to the east, which is not associated with uranium. The company is preparing an environmental impact assessment (EIA), but the Ministry of the Environment plans to expand the Natura 2000 in the area.

The world-class Sakatti deposit was discovered in 2011 by the AA Sakatti Mining Oy, a subsidiary of the British company Anglo American plc. The company prepared an EIA and plans an underground mine to avoid damage on Natura 2000 area of Viiankiaapa. Even then, the company has compensated biodiversity.

Because of Natura, companies have applied low impact mineral exploration technologies (LIMET: drones, plant, soil, and snow sampling, closed circuit drilling, portable drill rig and XRF device; Eerola 2021). They also practice active stakeholder engagement and communication, and projects seem to have been mostly favoured by local populations (e.g., Suopajärvi et al. 2019, Tuulentie 2019, Tulilehto & Suopajärvi 2021, Beland Lindahl et al. 2023). However, because of their association with Natura 2000 area, recreation, reindeer herding and uranium in the case of Rompas, projects have been opposed by the Finnish Nature Conservation Association (FANC), and the Save Viiankiaapa movement and reindeer herders in the case of Sakatti (Lassila 2020, Eerola 2022, Beland Lindahl et al. 2023). FANC is the major and the most important Finnish environmental non-governmental organisation (NGO), with an important role in mining-related struggles in

Finland (Eerola 2023). It supports and networks the local NGOs and movements all over the country.

Both companies will apply for mining permits with a new national Mining Act in force (from 1st June 2023). Therefore, municipalities will have a decisive influence on those permits regarding their zoning. So far, both municipalities have been favoring the projects, and Sodankylä Municipality has been developing a mining forum (Tuulentie et al. 2019) and a community benefit agreement which will be the first in Europe (Kotilainen et al. 2022).

The Sakatti and Rompas-Rajapalot are examples of mine and mineral exploration projects in Natura 2000 areas. Companies are adapting to such contexts by employing LIMET, and underground mining to minimise impact on the Viiankiaapa Natura 2000 area. Sakatti Mining Oy has also carried out an ecological compensation. Both deposits include critical raw materials (CRM) important to green energy transition. Due to its economic importance, Sakatti is a good candidate for a strategic deposit within the EU's CRM Act with a speeded permit process. However, because of its location within Natura 2000 area, this may complicate its permitting and intensify opposition to the project.

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REFERENCES

Beland Lindahl, K., Suopajärvi, L., Poelzer, G., Tulilehto, M. & Eerola, T. 2023. Factors affecting local attitudes to mineral exploration and mining: what's within the company's control? Resources Policy 84, 103715. Available at: https://doi.org/10.1016/j.resourpol.2023.103715

Eerola T. 2021. New low impact mineral exploration technologies and the social license to explore: insights from corporate websites. Cleaner Environmental Systems 3, 100059. Available at: https://doi.org/10.1016/j.cesys.2021.100059

Eerola, T. 2022. Corporate conduct, commodity, and place. Ongoing mining and mineral exploration disputes in Finland and their implications for the social license to operate. Resources Policy 76, 102568. Available at: https://doi.org/10.1016/j.resourpol.2022.102568

Eerola, T. 2023. The uranium and mining disputes in the context of environmental protest waves in Finland. The Extractive Industries and Society. (submitted)

Kotilainen, J. M., Peltonen, L. & Reinikainen, K. 2022. Community benefit agreements in the Nordic mining context: Local opportunities for collaboration in Sodankylä, Finland. Resources Policy 79, 102973. Available at: https://doi.org/10.1016/j.resourpol.2022.102973

Lassila, M. M. 2020. The Arctic mineral resource rush and the ontological struggle for the Viiankiaapa peatland in Sodankylä, Finland. Globalizations 18, 635-649. Available at: https://doi.org/10.1080/14747731.2020.1831818

Suopajärvi, L., Umander, K. & Jungsberg, L. 2019. Social license to operate in the frame of social capital exploring local acceptance of mining in two rural municipalities in the European North. Resources Policy 64, 101–498. Available at: https://doi.org/10.1016/j.resourpol.2019.101498

Thomson, I. & Boutilier, R. G. 2011. The social license to operate. In: Darling, P. (ed.) SME Mining and Engineering Handbook. Littleton, Co., 1779-1796.

Tulilehto, M. & Suopajärvi, L. 2021. Experienced Impacts of mining in Sodankylä. Follow-up study. University of Lapland: Rovaniemi, p. 31. Available at: https://lauda.ulapland.fi/bitstream/handle/10024/64813/Experienced%20Impacts%20of%20Mining%20in%20Sodankyl%c3%a4.pdf?sequence=1&isAllowed=y. [Accessed 31.5.2023]

Tuulentie, S., Halseth, G., Kietäväinen, A., Ryser, L. & Similä, J. 2019. Local community participation in mining in Finnish Lapland and northern British Columbia, Canada – practical applications of CSR and SLO. Resources Policy 61, 99–107. doi:10.1016/j.resourpol.2019.01.015

INTELLIGENT DIGITAL TOOLBOX TOWARDS MORE SUSTAINABLE AND SAFER EXTRACTION OF MINERAL RESOURCES

by

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Europe's industry and economy depend on a secure access to many commodities. Securing sustainable access to Critical Raw Materials (CRMs), is high importance for the Europe Union (EU) economy. Renewable energy, e-mobility, aerospace and defence technologies depend on the availability of CRMs (Grohol et al. 2023, European Commission & Joint Research Center 2020), and China is the dominant supplier for the majority of the CRMs, while the EU's global share is more than 0.5% (Grohol et al. 2023) However, the EU is confronted with a number of technological and environmental challenges along the entire production value chain of primary and secondary raw materials. NetHelix demonstrates in real-life settings toolbox of new technologies for automating and streamlining the extraction process, taking advantage of mineral and waste deposits via novel processing methods, maximising efficiency, reducing waste production, increasing environmental and human health and safety.

The NetHelix technologies will be tested first and validated in a controlled environment, in the underground mine facilities at "Reiche Zeche" in Germany, as well as at the testing facilities and mine of SANDVIK. Following the successful technology validation, and after performing an iterative optimisation based on initial findings; the project will then demonstrate the NetHelix platform at more than five sites (Process plants, surface and underground mines). Having the pre-pilot sites (Reiche Zeche & SANDVIK test site) give to the consortium the luxury time to develop, test, and optimise the tools and technologies before implementing them into the other mine sites.

Over the duration of the project (2023–2026), NetHelix has set clear objectives. The first one focuses on the development and validation of environmentally friendly, remote-controlled, and automated machinery for the EU mining industry. Through the use of advanced technologies, NetHelix aims to improve operational efficiency while reducing the environmental footprint of mining activities. Also, development and demonstration of health and safety sensors for mining operations. These sensors will contribute to a secure and healthy work environment, ensuring the well-being of mining industry personnel.

Moreover, an additional objective aims to minimise downtime and enhance operational productivity through effective maintenance practices facilitated by a predictive maintenance platform. By leveraging data and analytics, this platform

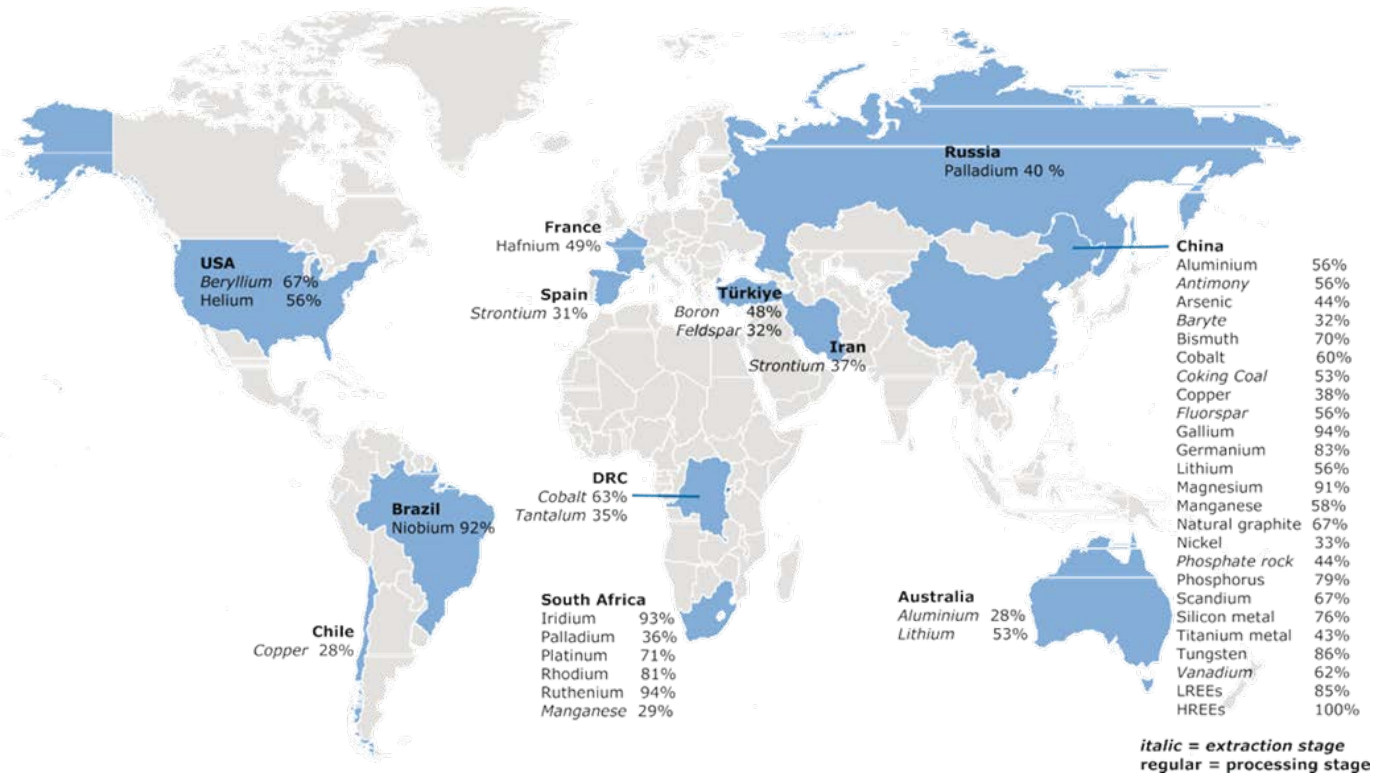

Fig. 1. Countries accounting for largest share of global supply of CRMs.

will optimise maintenance processes and improve overall efficiency in mining operations. NetHelix recognises the importance of informed decision-making. Another objective involves the development of an advanced Decision Support System (DSS) that empowers decision-makers in the mining sector. Utilising sophisticated algorithms and data analysis techniques, the DSS will enable informed choices that maximise resource efficiency and production yield, thereby promoting sustainable and resource-efficient mining practices.

Sustainability is a core focus of NetHelix. Another objective centres around the development and demonstration of novel and eco-friendly mineral extraction schemes. By prioritising responsible resource management and minimising the ecological footprint of mining operations, NetHelix aims to ensure the long-term sustainability of the mining industry and is committed to facilitating the commercial exploitation of its innovative solutions. An additional objective involves the implementation of advanced business models tailored to meet the specific needs of mining companies. NetHelix intends to establish a greener and more responsible global economy by fostering collaboration, engaging stakeholders, and promoting broad acceptance and adoption of the project's concepts and technologies.

NetHelix will run for 3.5 years in order to allow sufficient time for all development and integration tasks, but also for the appropriate validation of the approach, which is expected to take slightly longer than average due to the specific conditions that apply to validation in real industrial settings in mines. The work plan has been structured in such a way as to achieve rapid delivery of the first results and to allow gradual validation of the approach for each component, leading to an overall validation of the NetHelix platform. Overlapping of work packages has been planned to avoid delays in case of unforeseen delays in any single task.

REFERENCES

European Commission & Joint Research Center 2020. Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study. Luxembourg: European Union.

Grohol, M., Veeh, C., DG GROW & European Commission 2023. Study on the Critical Raw Materials for the EU 2023. Luxembourg: European Union.

CHARACTERISATION OF REE IN LOW-GRADE DEPOSITS: NEW LA-ICPMS SEMI-QUANTITATIVE APPROACH

by

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Owing to the intensive mining activities of recent decades, a global decline in resources from conventional high-grade deposits has been observed. This decline and the growing need for critical raw materials (CRMs) for clean technologies have led to a gradual reconsideration of mining strategies and, hence, the development of an interest in so-called non-conventional resources (McLellan et al. 2016b). Beyond gas and oil deposits, non-conventional resources include a wide range of low-grade, high-tonnage mineral bodies, including polymetallic nodules, ion-adsorption clays, black shales, and sedimentary phosphorites (McLellan et al. 2016a). The characterisation and extraction of valuable metals from these deposits is a challenge for the industry in terms of sustainable mining and mineral characterisation. This applies to nonconventional REE sources such as sedimentary phosphorite deposits (Embso et al. 2014, McNulty 2022), in which concentrations may be below the detection limits of conventional FE-SEM EDS automated mineralogy techniques (Schulz et al. 2020).

Phosphorite deposits typically contain more than 18% P_2O_5, mainly via carbonate fluorapatite, which shows highly variable 1) chemical composition due to the numerous anionic and cationic substitutions related to the specific genetic environment and 2) mineralisation type including nodules, ooids, concretions, biogenic phosphates (Schulz et al. 2020). Therefore, the enrichment of P and REE in phosphorites varies significantly, and the viability of resource and beneficiation studies will depend on a comprehensive characterisation of the mineralisation of REE. This study aims to apply a recent LA-ICP-MS mapping and processing method to Estonian shelly phosphorites in order to determine controlling factors for REE enrichment and to semi-quantify the REE resources in apatites.

The Drost technique used in this study is an LA-ICP-MS method based on the ablation rasters combined into the distribution map of a measured isotope or element (Godet & Föllmi 2021). Selection criteria are then used to extract zones of interest within the mapped area (e.g., Ca and P will be used as criteria to extract apatites). The pixels within the region of interest will be divided into groups applying an empirical cumulative distribution function (ECDF) and using the val-

ues of a selected channel in ascending order (Drost et al. 2018, Chew et al. 2021). Thus, this method allows the isolation of the different phases of the materials, the extraction of individual chemical signals, and the obtention of a stepwise representative distribution, emphasising compositional variations of an element or isotope (Petrus et al. 2017). Three shelly phosphorite samples were processed for the study (Fig. 1): a sample from the Aseri deposit (a1) and two from the Toolse deposit (b1, c1). They were selected because they originate in the Maardu Member, the richest horizon in apatite and REE (Graul et al. 2023). The mineralogy of this layer is primarily trimodal between apatite, carbonate cement and quartz. The whole-rock analyses suggest significant REE enrichment in these materials. However, no data are currently available to distinguish shell and carbonate signals, and it is thus necessary to ascertain which phases contain which REEs and which concentration (Graul et al. 2023). The elements selected for analysis are REEs, along with other trace elements including Fe, Mn, Sr, Ti, Zn, Pb, U, and Th. REE enrichment was investigated according to Sr, Mn and U, diagenetic and alteration tracers, and Ce, the most abundant REE.

ECDF mapping in Figure 1 show that the carbonates are strongly depleted in U, Sr and Ce compared to the apatite area and present traces of Fe and Mn zonation. Therefore, this material is of no economic interest. The apatites present a complex chemistry related to the internal structure and local alteration of the shell fragments. Figure 2 illustrates the variations of post-Archean Australian Shale (PAAS) normalised REE patterns in the Aseri sample. Firstly, the REE spectrum appears to show a homogeneous trend with MREE enrichment typical of diagenetically enriched apatite [10]. However, the degree of enrichment fluctuates significantly depending on the studied concentrations (Fig. 2a). For Sr, there is an initial positive and progressive covariance trend between REE and Sr, but the richest signals in REE (up to 80 fold) are the poorest in Sr. For Mn, conversely, there is an initial negative covariance between REE and Mn, followed by strong depletion at the most enriched levels. The same observations can be drawn from Fig. 1a2, where relatively stable Sr and Mn contents can be noted, followed by Sr and Ce enrichment and Mn depletion in the 'cracks', and high Sr and Mn depletion along with a notable Ce level in the most altered fragments. The behaviour of REEs, according to U, is different. The majority of the steps remain within the same range of REE and U content. It is only from step 110 (Fig. 2b) onwards that an intense increase in the U and REE content is observed. This trend is mirrored on the U and Ce ECDF maps, where the richest zones, i.e., the altered fragments and the edges of the main shell, correlate. These data demonstrate a multistage enrichment of the REEs: a first general trend towards medium-intensity diagenetic uptake (up to ±20 fold) and a second trend towards intense alteration-related uptake (up to 120 fold).

Based on these findings, the average chemical composition and multivariate analysis of apatites were determined by distinguishing the steps between a first enrichment stage according to Sr, as the 'mean apatite' and a second stage according to U, as the 'altered apatite' (Table 1 and Fig. 3). Whilst these calculations involved two distinct treatments, the segregation was effective, resulting in a frequency of ±93% (n=98) for Sr and ±7% (n=9) for U. The mean apatite has a REE concentration of 2046±207 ppm and low toxic metals, with only Pb and Th loadings following the trends of Sr and REE trends. The altered apatite has a much higher REE concentration: 7021±3533 ppm. The U concentration reached 284±113 ppm, although the toxic metals remained in the same range. Zn, Th and U are related to the REE enrichment. Th alone increased from 0 to 20 ppm. However, these levels remain low for apatites, providing an advantage for later beneficiation processes.

The image-based LA-ICP-MS technique is fast and cost-effective compared to traditional methods with similar detection limits (Petrus et al. 2017). It allows a good visualisation at different scales, representative measurements and a first approach to semi-quantifying element concentrations. This tool has great potential to substitute applied mineralogy technologies that are not applicable for this type of material. Coupled with other techniques such as imaging tools and database development, this method will provide insight into understanding the factors influencing chemical processes in low-grade sedimentary ore bodies and determine their potential economic interest.

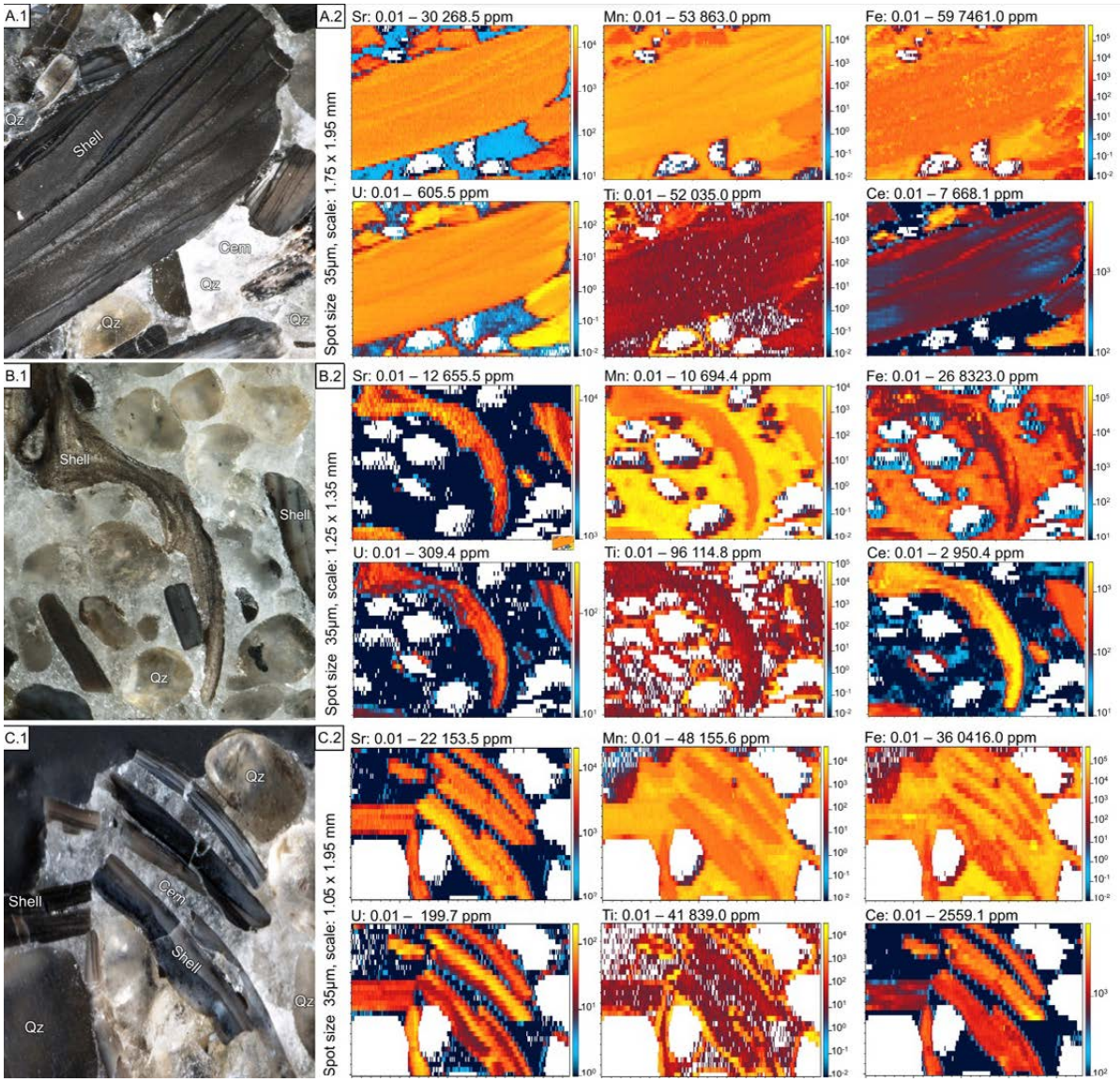

Fig. 1. Microphotographs and LA-ICP-MS ECDF mapping of the three studied phosphorites samples for the following elements: Sr, Mn, Fe, U, Ti, and Ce.

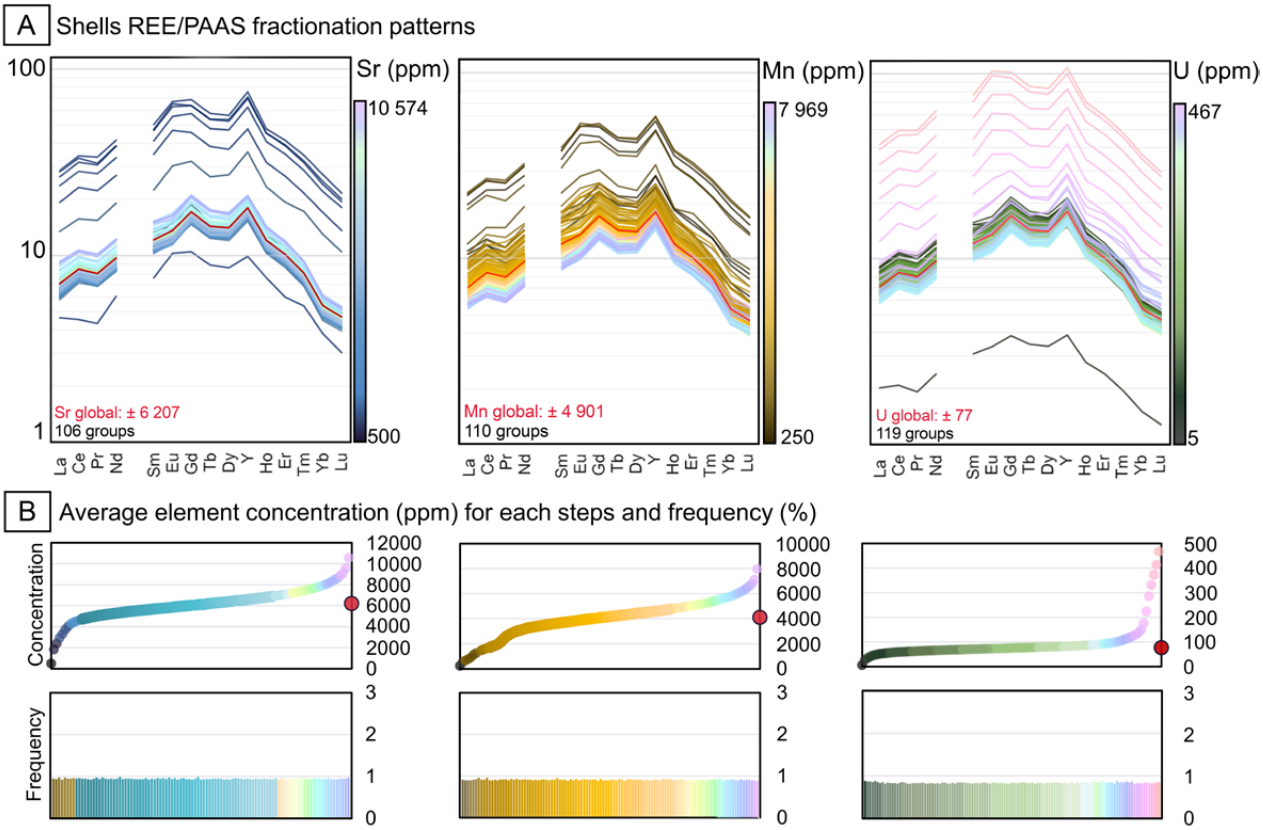

Fig. 2. a) REE fractionation pattern normalised to PAAS for ECDF treatment following Sr, Mn and U. Number of steps and average focus elements concentrations are provided. b) Average element concentration and frequency, based on pixel content, for each calculated step.

Table 1. Average concentrations and associated standard deviations for the 1st – Sr enrichment (n=98, ±93%), 2nd – U enrichment (n=9, ±7%). Concentrations and standard deviations are expressed in percentage for Sr, Mn and Ti; and in ppm for all other elements.

Sr	Mn	Fe	Ti	Zn	Pb	Th	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Ho	Er	Tm	Yb	Lu	∑REE
(%)			(ppm)																				
Sr Calculations – 1st enrichment																							
0.64	0.43	0.76	27	19	40	0.3	76	260	660	69	300	65	14	78	11	60	469	12	28	3	14	2	2046
0.12	0.04	0.09	3	2	8	0.4	9	32	70	7	8	7	1	8	1	5	38	1	2	0	1	0	207
U Calculations – 2nd enrichment																							
0.4	0.2	0.9	54	28	70	20	284	1624	876	2211	239	1066	231	60	261	36	1624	39	97	11	58	7	7021
0.1	0.1	0.6	11	7	56	16	113	782	4441	1104	125	576	120	33	33	18	782	19	46	5	28	3	3533

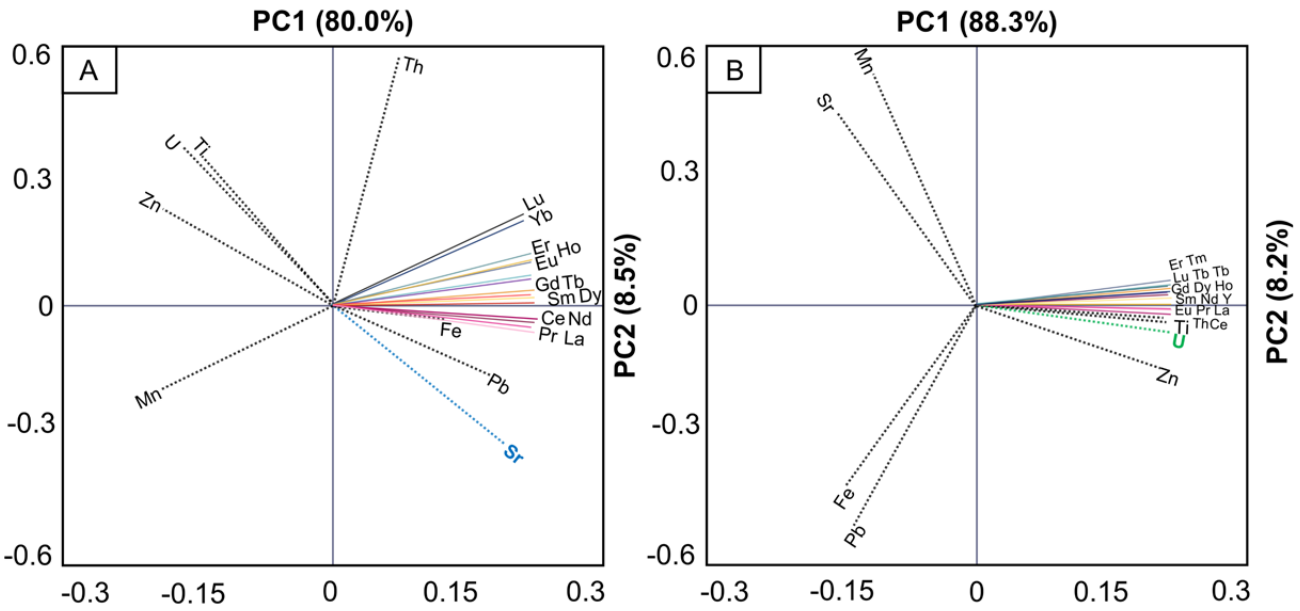

Fig. 3. PCA plots for the 1st – Sr enrichment (n=98) and 2nd – U enrichment (n=9).

REFERENCES

Chew, D., Drost, K., Marsh, J. H. & Petrus, J. A. 2021. LA-ICP-MS imaging in the geosciences and its applications to geochronology. Chemical Geology 559, no. 119917.

Drost, K., Chew, D., Petrus, J. A., Scholze, F., Woodhead, J. D., Schneider, J. W. & Harper, D. A. T. 2018. An Image Mapping Approach to U-Pb LA-ICP-MS Carbonate Dating and Applications to Direct Dating of Carbonate Sedimentation. Geochemistry, Geophysics, Geosystems, 19, 4631–4648.

Embso, P., McLaughlin, P., Breit, G. N., du Bray, E. A. & Koenig, A. E. 2014. Rare Earth Elements in Sedimentary Phosphate Deposits: Solution to the Global REE Crisis? Gondwana Research 27(2), 776–785.

Godet, A. & Föllmi, K. B. 2021. Sedimentary phosphates deposits. Encyclopedia of Geology. Elsevier, 922–930.

Graul, S., Kallaste, T., Pajusaar, S., Urston, K., Gregor, A., Moilanen, M. Ndiaye, M. & Hints, R. 2023. REE+Y Distribution in Tremadocian Shelly Phosphorites (Toolse, Estonia): Multi-Stages Enrichment in Shallow Marine Sediments during Early Diagenesis. Journal of Geochemical Exploration 254, 107311. Available at: https://doi.org/10.1016/j.gexplo.2023.107311

McLellan, B., Corder, G., Ali, S. & Golev, A. 2016a. Rare metals, unconventional resources, and sustainability. Special Paper of the Geological Society of America 520, 57–65.

McLellan, B. C., Yamasue, E., Tezuka, T., Corder, G., Golev, A. & Giurco, D. 2016b. Critical Minerals and Energy–Impacts and Limitations of Moving to Unconventional Resources. Resources 2016, 5, 19.

McNulty, T., Hazen, N. & Park, S. 2022. Processing the ores of rare-earth elements. MRS Bulletin 47, 258–266.

Petrus, J. A., Chew, D. M., Leybourne, M. I. & Kamber, B. S. 2017. A new approach to laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS) using the flexible map interrogation tool 'Monocle'. Chemical Geology 463, 76–93.

Schulz, B., Sandmann, D. & Gilbricht, S. 2020. SEM-Based Automated Mineralogy and Its Application in Geo- and Material Sciences. Minerals 10, 1004.

PETROPHYSICS AS A TOOL IN PEGMATITE EXPLORATION – UTILISING A NEW AND OPEN-ACCESS DATABASE

by

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Petrophysical data are an important asset for the exploration of mineral deposits. Only geophysical methods are able to detect or follow buried deposits at depth, that is if a contrast in physical properties of the ore and wall rocks exists *and* if this contrast is large enough to be resolved by the respective method. Knowledge of the petrophysical properties facilitates the choice of suitable geophysical exploration methods and enables a more efficient exploration workflow.

The Horizon 2020 GREENPEG project (GA no. 869274) focuses on small-scale granitic pegmatite deposits and their efficient and sustainable exploration (Müller et al. 2022). These deposits are of interest owing to their content of high purity quartz, lithium, rare earth elements and other critical minerals that are indispensable for the energy transition and high-tech industry. As part of the development of innovative and streamlined exploration workflows for this type of deposits, petrophysical data from different pegmatite occurrences with varying characteristics were collected and analysed.

In exploration, pegmatites are often difficult to detect with geophysical methods (Bradley et al. 2017, Galeschuk & Vanstone 2007, Steiner 2019) as they are not characterised by reasonably high or low physical properties. Nevertheless it is common to use geophysical methods for an indirect localisation of pegmatites (e.g., airborne surveys, e.g., Ahtola et al. 2015). More and more studies are being published that also report the successful direct localisation of the pegmatites (e.g., Winsomeresources 2022). Potential lies in a detailed and systematic study of the physical contrast of the pegmatites and their surrounding wall rocks. This can be provided by a petrophysical approach and the statistical evaluation of a corresponding database. Data sets of this kind are not yet known to the authors. If a contrast exists, a non-invasive geophysical method might be able to resolve it.

Within GREEPEG we analysed petrophysical data collected at three demonstration sites located in Austria, Ireland, and Norway. The sites host NYF- and LCT-type pegmatites (Niobium-Yttrium-Fluorine and Lithium-Cesium-Tantalum respectively; classification after Černy 1991) and were chosen due to the variation in deposit genesis, geology, tectonic and climatic setting, topography, and vegetation, to be representative for European pegmatite deposits. Data analysis

showed that all three pegmatite deposits are also petrophysically different. At the same time, all three sites revealed a number of physical properties with contrasts between the pegmatites and their host rock(s).

Wolfsberg/Austria: The LCT-pegmatites in the Austrian alps around Wolfsberg are mainly deposited in amphibolite and mica schist host rock. Both can be distinguished by several petrophysical parameters, such as density and magnetic susceptibility, but also natural/spectral gamma and chargeability. The pegmatites have comparably lower densities and susceptibilities than their host rocks and can be distinguished. Differences in petrophysical parameters between host rocks and pegmatites become more pronounced when distinguishing between amphibolite-hosted and mica schist-hosted pegmatites. Natural gamma, uranium, and density show clear contrasts between the amphibolite-hosted pegmatite and its host rock, where the pegmatites have significantly higher values. The mica schist-hosted pegmatite on the other hand shows a clear drop in chargeability compared to its host rock.

South Leinster/Ireland: These pegmatites are mostly emplaced in granite. They are differentiated by their mineralisation into spodumene, albitised, and (barren) granitic pegmatite. The pegmatites can be distinguished from the granitic wall rock, e.g., by the thorium content which is higher in the granite and shows a clear contrast. Uranium shows a less prominent contrast where the granite has lower values than the pegmatites. Another parameter to distinguish between pegmatites and the granitic host rock is seismic velocity (Vp and Vs). Pegmatites have an average lower Vs velocity than the surrounding granite. This property contrast is prominent in most boreholes but in some the contrast is rather insignificant. When looking at the pegmatites in detail it shows that (barren) granitic pegmatites have rather similar Vp and Vs velocities with the granite, in contrast to the mineralised pegmatites. Spodumene pegmatites generally have higher Vp and Vs velocities, and albitised pegmatites have lower velocities than the barren pegmatites. Looking even more closely we see that the Vs velocity drops for albitised pegmatite and can likely allow distinguishing between the different mineralised pegmatites.

The data analysed in this study are available as part of a new and freely accessible petrophysical database that was compiled and released by the GREENPEG project: the EuroPegDB database for European pegmatite deposits and their wall rocks (Haase et al. 2022, Haase & Pohl 2022). In total, petrophysical data from test and demonstrations sites in 5 countries were collected: Austria, Ireland, Norway, Portugal, and Spain. Measurements were performed in the laboratory on samples from outcrops and drill cores, as well as along boreholes via geophysical wireline logging. The latter data were extracted from the continuous recordings following a special procedure to secure accuracy. The data set contains supplementary meta-information in addition to the petrophysical measurements, such as sample identifiers, photographs, locations and coordinates, sample descriptions, lithology codes, and variable names. The data are machine-readable and eligible for quantitative analyses to discover trends and correlations for different deposit types. In addition, the complementary spatial and meta-information allow data integration in subsurface and deposit models. It is the first data set of its kind and freely accessible through the open data repository Zenodo. This repository assigns unique digital object identifiers (DOI) and supports a versioning scheme for its content, allowing to update the database when new data becomes available. Previous versions remain accessible and referable. All of this, together with the way the database is structured (Fig. 1), supports the FAIR data initiative. The EuroPeg database only contains data collected during the project phase (as at September, 2023). Seeing the usefulness and importance of such a data set, the authors plan to maintain and update the database with more content from

European pegmatite occurrences. Here, contributions from interested users and readers are highly appreciated.

Quantitative analysis of the petrophysical data shows that pegmatites can indeed be distinguished from their wall rocks in terms of physical properties and geophysical methods. In this study we got indicators, e.g., for ERT, IP, seismics, gravity, magnetics, and gamma spectrometry. However, not all discovered property contrasts might be usable in field applications and for exploration. In the end, the applicability and success of geophysical methods still depends on the thickness, orientation, and depth of the buried pegmatite. Through the gathered petrophysical knowledge, the confirmation of physical property contrasts, and their use in choosing the right exploration methods, this study shows that the database is a powerful tool. The visual inspection of borehole logging data (composite logs) is intuitive and allows identification of different lithologies via visual inspection and correlations. Using the extracted petrophysical data classified by lithological intervals allows for a quantitative analysis and recommendation for possible ground-borne geophysical methods for exploration, with an indication of the required resolution (and survey design) dictated by the observed property contrasts. A prerequisite for geophysical exploration however is a known pegmatite occurrence. This may be a single outcrop or a drillhole intersection. Collecting petrophysical data should be the immediate next step. After analysing outcrop samples or wireline logging results of one drill hole, valuable information specific to the deposit under investigation is available and can be used to guide the further exploration strategy. Geophysics can then aid it outlining or tracing this known appearance or it can aid in finding similar pegmatites in close vicinity. And even if the pegmatite itself is not resolvable from the data, knowledge of the physical properties might allow to outline the host rock against the country rock and with that aid in the imaging of the deposit.

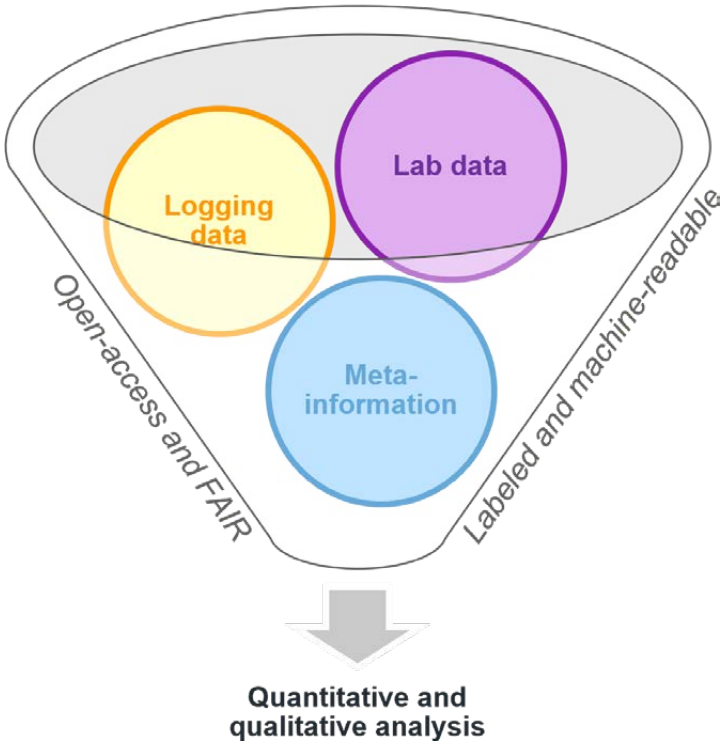

Fig. 1. Schematic illustration of the database concept.

REFERENCES

Ahtola, T., Kuusela, J., Käpyaho, A. & Kontoniemi, O. (eds) 2015. Overview of Lithium Pegmatite Exploration in the Kaustinen Area in 2003–2012. Geological Survey of Finland, Report of Investigation 220. 28 p. Available at: https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_220.pdf

Bradley, D. C., McCauley, A. D. & Stillings, L. M. 2017. Mineral-Deposit Model for Lithium-Cesium-Tantalum Pegmatites. U.S. Geological Survey, Scientific Investigations Report 2010–5070–O. 48 p. Available at: https://doi.org/10.3133/sir20105070O

Černý, P. 1991. Rare-element granitic pegmatites. Part I: Anatomy and internal evolution of pegmatite deposits. Geosci. Can. 18, 49–81.

Galeschuk, C. & Vanstone, P. 2007. Exploration Techniques for Rare-Element Pegmatite in the Bird River Greenstone Belt, Southeastern Manitoba. In: Milkereit, B. (ed.) Proceedings of the Exploration 07: Fifth Decennial International Conference on Mineral Exploration, Toronto, ON, Canada, 9–12 September 2007, 823–883.

Haase, C. & Pohl, C. M. 2022. Petrophysical Database for European Pegmatite Exploration –EuroPeg. Minerals 12, 1498. Available at: https://doi.org/10.3390/min12121498

Haase, C., Brönner, M., Pohl, C. M., Osinska, M. & Gellein, J. 2022. EuroPeg_PetroDB: A petrophysical database of European pegmatite ores and wall rocks. (2.0) [Data set]. Zenodo. Available at: https://doi.org/10.5281/zenodo.7347371

Müller, A., Reimer, W., Wall, F., Williamson, B., Menuge, J., Brönner, M., Haase, C., Brauch, K., Pohl, C., Lima, A., Teodoro, A., Cardoso-Fernandes, J., Roda-Robles, E., Harrop, J., Smith, K., Wanke, D., Unterweissacher, T., Hopfner, M., Schröder, M., Clifford, B., Moutela, P., Lloret, C., Ranza, L. & Rausa, A. 2022. GREENPEG – Exploration for pegmatite minerals to feed the energy transition: First steps towards the Green Stone Age. In: Smelror, M., Hanghøj, K. & Schiellerup, H. (eds) The Green Stone Age: Exploration and Exploitation of Minerals for Green Technologies. London: Geological Society, Special Publications 526. Available at: https://doi.org/10.1144/SP526-2021-189

Steiner, B. M. 2019. Tools and Workflows for Grassroots Li–Cs–Ta (LCT) Pegmatite Exploration. Minerals 9, 499. Available at: https://doi.org/10.3390/min9080499

Winsomeresources 2022. Geophysical gravity survey reveals high priority drill targets at Cancet. ASX release 19 October 2022, ASX:WR1; FSE:4XJ. 3p.

INTEGRATED MULTI-SCALAR STRUCTURAL-GEOCHRONOLOGICAL STUDIES OF MINERAL DEPOSITS: EXAMPLES FROM MOLYBDENITE DEPOSITS IN SOUTH NORWAY

by

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The spatial and temporal relationships between orogen-scale tectonic evolution and the evolving geometric, kinematics and timing of mineralisation is an aspect of mineral exploration that, globally, has received rather limited focus. In Scandinavia, this is an aspect of geodynamics that is at the forefront of grass-roots mineral research. We focus on the nature of molybdenite deposits in the Sveconorwegian Orogen of southern Norway. The N-S elongated, several kilometre-wide Knaben Zone hosts abundant molybdenite deposits and is located within the late Mesoproterozoic Sirdal Magmatic Belt (SMB), a large, recently identified N-S elongated batholith. The SMB granitoids are generally undeformed to weakly deformed, with strain concentrated along up to 30m wide, shallowly east-dipping, N-S trending xenolith screens which appear to be contacts between different pulses of the SMB batholith injection. While these zones of enhanced deformation are unlike conventional shear zones, we observe consistent kinematics and duplex geometries in veins which display top-to NW thrust kinematics.

Molybdenite is both associated with the magmatism at ca. 1030–1040 Ma and the thrusting, which we interpret to have formed during the emplacement of the different granite sheets. Molybdenite is found within microveins in the duplex structures and sub-horizontal pegmatites intimately related to thrusting. Re-Os dating in the molybdenite gives ages ranging from 1050–980 Ma. Detained mapping around the now defunct Knaben II mine shows a complex thrust duplex array striking NS and up to several hundred metres wide hosting all of the molybdenite. Further west in the orogen, we have identified, a flat-lying, E-dipping, 15 km wide, ductile extensional zone, juxtaposing the exhumed Rogaland Anorthosite Complex and high-grade rocks to the west from unmetamophosed rocks in the footwall. This is termed the *Rogaland Extensional Detachment*. U-Pb dating of leucosomes in extensional pull-aparts are dated to 950–935 Ma and represents the late orogenic extension documented in other parts of the orogen.

We document several molybdenite deposits with brittle to ductile extensional kinematics which we interpret as reflecting the hangingwall disintegration of the Rogaland Detachment Zone. Re-Os dating from molybdenite in quartz veins records crustal extension from ca. 980–930 Ma. Therefore, comparing the eastern part of the orogen with the western part we document variations in the timing, kinematics, geometry, spatial distribution, and tectonic style of molybdenite mineralisation across the orogen.

ORCHESTRATING THE DIGITAL TRANSFORMATION IN MINING: INTRODUCING PROJECT MINE.IO

by

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INTRODUCTION

The advent of the fourth industrial revolution has stimulated a paradigm shift in supply chain management in many industries, including the mining sector. Within this transformative environment, Industry 4.0 technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Big Data, robotics, and cloud computing have emerged as critical tools for increasing economic performance and productivity (Pereira & Romero 2017, Aziz et al. 2020). However, the growing social and environmental responsibility obligations require more than just technological advancements: they necessitate a holistic approach to sustainable mining operations. This study introduces Mine.io, an innovative digital ecosystem that integrates the entire mining value chain, from initial resource exploration to extraction, processing, waste management, and post-mining activities.

SUSTAINABLE MINING APPROACH OF MINE.IO

Mine.Io employs a unique manufacturing system architecture within a cloud environment to implement a digital twin of a mining operation (Fig. 1). This facilitates asset and process equipment optimisation through embedded predictive analytics. Designed to be more than a mere technological overlay, the ecosystem establishes a suitable data infrastructure that fosters inter-enterprise collaboration and promotes data openness and sharing. Moreover, Mine.io distinguishes itself by embedding sustainability at its core, incorporating strategies for "low-impact mining" and a circular economy with an emphasis on energy optimisation. This

ensures socially conscious profit generation and enhances safety for front-line workers.

To validate the robustness and applicability of the Mine.io ecosystem, rigorous testing will be conducted at four operational and two historic mining sites across five European Union countries. Through its amalgamation of advanced technologies, collaborative frameworks, and responsible practices, Mine.io aspires to initiate a new paradigm of sustainable and efficient mining operations.

CONSORTIUM

The Mine.io Consortium comprises 25 partners from 11 distinct EU countries, including Cyprus, Finland, Germany, Greece, Hungary, Italy, Norway, Poland, Portugal, Spain, and Sweden. These partners bring together a multifaceted array of expertise in exploration, extraction, mineral processing, and digital waste management technologies. The Consortium ensures a highly complementary and well-balanced partnership. Each member is a renowned specialist in their respective field, yet they collectively share a vested interest in accelerating the digital transformation of the mining sector. The project is funded by the Horizon Europe Programme.

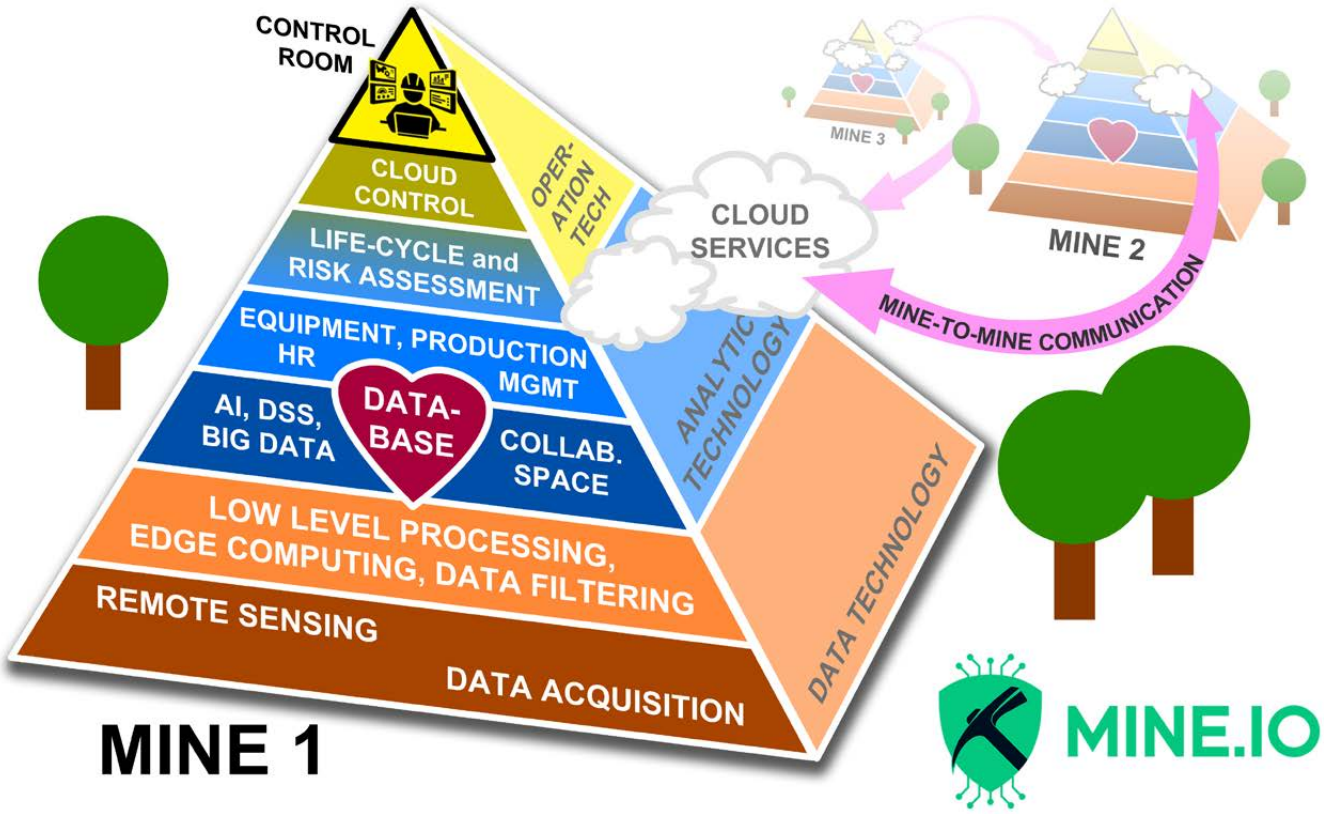

Fig. 1. A schematic view of the Mine.io vision of future mine architecture. The entire system is based on a cloud services system connected to automated sensors as well as on a novel mining ecosystem of sharing, interconnection, and open cooperation. This allows the effective sharing of innovations and best practices while maintaining trade secrets and a competitive economy. Image by Mine.io consortium.

OBJECTIVES

The primary objective of the Mine.io project is to provide a state-of-the-art mine manufacturing system architecture that operates within a cloud environment. This technological framework aims to facilitate data sharing, interconnection, and collaborative endeavours among various stakeholders in the mining industry. To materialise this vision, a further objective is to establish a unified big data collaboration platform. This platform intends to further encourage data openness and sharing, enhancing the collaborative environment among various mining enterprises. Through these objectives, Mine.io aspires to redefine the standard practices in the mining industry, emphasising both technological innovation and cooperative ventures.

Additionally, Mine.io is committed to enhancing underground safety measures. One of the key aspects of this commitment is reducing employee fatigue by increasing automation. The project also focuses on elevating production levels and advancing sustainable mining by optimising various technologies. These technologies pertain to diverse operational facets, including mineral exploration, mineral beneficiation, smelting processes, and workforce scheduling.

DEPLOYED TECHNOLOGIES

In the Mine.io project, an array of cutting-edge technologies undergoes development, demonstration, and rigorous validation. Specifically, the technological suite encompasses advanced mineral exploration methodologies such as muon detectors for muography, autonomous underwater vehicles equipped with research instruments for in-situ exploration in flooded open pits, and airborne drones designed for electromagnetic and magnetic surveys. Additional technologies focus on enhancing drill core analysis through X-ray techniques and optimising drilling processes. In the realm of extraction, the project aims to introduce and improve technologies for mineral processing. These entail smart sorting systems prior to beneficiation, AI-driven optimisation of ore flotation processes, sensor-integrated digital twins for smelting operations, and waste management solutions.

The project also focuses on elevating operational efficiencies in underground mobility and logistics. Novel solutions are being developed for the electrification and autonomous operation of underground trucks, thereby augmenting the logistical aspects of mining. Furthermore, the principle of swarm intelligence is being applied to bolster mine logistics. Via these technological advancements, the project concentrates on refining production scheduling and optimising logistics, thereby ensuring a more streamlined and efficient mining operation.

Mine.io also integrates predictive maintenance modules that utilise advanced machine learning algorithms for three tiers of analytics: descriptive, predictive, and prescriptive. These algorithms analyse data generated by sensors to produce actionable insights. The predictive maintenance approach employs real-time operational data to forecast potential asset failures. By anticipating issues before they escalate into failures, companies can minimise operational downtime and reduce repair costs. Such an optimisation is made possible through the utilisation of cutting-edge condition-monitoring sensor technologies.

IMPACT AND OUTCOMES

Economic and Technological Impact – The Mine.io project aims to be at the forefront of sustainable and smart mining technologies, focusing on the full spectrum of mineral exploitation stages – exploration, extraction, processing, and waste management. By integrating digital, robotic, and eco-friendly technologies, the project offers a comprehensive framework that is not merely a technological leap but also a sustainable and economically viable alternative to conventional and sometimes outdated mining practices. This approach will significantly accelerate the smart digital transition in exploiting EU mineral resources.

Societal Impact – The mission of Mine.io transcends economic and technological gains; it envisions a society where mining is safe, eco-friendly, and efficient. The project is particularly committed to electrifying underground mobility resources to minimise the CO_2 footprint and eliminate the use of fossil fuels. It also focuses on enhancing worker safety through its various operational improvements. The project's digital simulations and data-driven technologies also promise to reduce operational costs while enhancing efficiency, thus contributing to broader societal benefits.

Scientific Impact – The scientific contributions of Mine.io are manifold. The project will introduce novel methods, technologies, and processes that support digitisation and automation in raw material production. By offering a holistic solution that encompasses the complete life cycle of mining operations, the project will lead to more resilient, sustainable, and secure value chains for critical raw materials in the EU. This aligns well with the twin green and digital transformations the EU is pursuing.

Contribution to EU Policies and Objectives – Mine.io is fully aligned with the objectives of the EU by introducing environmentally friendly technologies to establish stable and reliable sources of critical raw materials within the EU. The tools and technologies developed will represent a new form of digital sustainability using digital means to achieve sustainable outcomes.

SUMMARY

The Mine.io project stands at the forefront of the fourth industrial revolution, harnessing Industry 4.0 technologies to revolutionise supply chain management in the mining sector. Operating within a cloud-based environment, Mine.io employs a unique manufacturing system architecture to optimise both asset and process equipment through predictive analytics. The project extends beyond mere technological solutions by embedding sustainability at its core, thereby fostering socially conscious profit generation and enhancing safety measures. Rigorous testing across multiple European Union countries validates the system's robustness and applicability to diverse mining operations.

The Consortium, composed of 25 partners from 11 EU nations, facilitates a well-balanced partnership, driving the digital transformation of the mining sector by leveraging each member's expertise. Mine.io aims to establish a unified big data collaboration platform to promote data openness and inter-enterprise collaboration, targeting both technological innovation and cooperative ventures. Furthermore, the project is committed to advancing underground safety and operational efficiencies, including the optimisation of extraction and processing

technologies. Through its comprehensive approach, Mine.io aspires to redefine standard practices in the mining industry and establish a new era of sustainable and efficient mining operations.

REFERENCES

Aziz, A., Schelén, O. & Bodin, U. 2020. A Study on Industrial IoT for the Mining Industry. Synthesized Architecture and Open Research Directions. IoT 2020, 1(2), 529–550.

Pereira, A. C. & Romero, F. 2017. A review of the meanings and the implications of the Industry 4.0 concept. Procedia Manufacturing 13, 1206–1214.

HORIZON EUROPE PROJECT AGEMERA

by

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The digital and green transition aims to bring Europe as a NetZero CO_2 producer by 2050. The need for raw materials is increasing to reach these goals, especially in electrification of mobility, metal processing, renewable energy production and hydrogen economy. Some material needs can be met with recycling, some by substituting current critical raw materials (CRMs) with more abundant materials, but primary raw materials are still needed to meet the demand. However, resourcing must be done responsibly, including people, the environment and the economy. The EU-funded AGEMERA project studies the CRM potential within Europe and Zambia, developing novel AGEMERA AI-aided platforms, exploration technologies, and new tools for social sciences to study people´s perceptions of mining and exploration. The project also raises awareness of how metals and raw materials are present in our everyday lives and where the materials come from. Responsible sourcing is also one of the EU´s goals. The project´s technologies and studies are piloted in five trial areas in Europe and one in Zambia. The project and its status are presented in this paper.

INTRODUCTION

The European Union's green and digital transition goals are crucial in advancing European decarbonisation efforts. These significant changes involve shifting to electric transportation, moving from carbon-based energy production to renewable sources, and innovating new technologies and strategies for the efficient distribution of clean energy (Muench et al. 2022). However, achieving these goals faces a notable challenge – manufacturing environmentally-friendly technologies requires substantial amounts of various metals and minerals.

While recycling initiatives, circular economic models, and research-driven substitution of critical materials contribute partially to the supply chain, their impact falls short compared to the projected future demands (Grohol & Veeh 2023). A consensus acknowledges the urgent need for increased raw material production. Additionally, essential raw materials are classified as "critical" due to economic

and supply availability factors. Currently, the EU's native supply of several primary CRMs represents a fraction, less than 3%, underscoring the Union's significant dependence on imports from countries like China, Russia, and South Africa.

Given the changing global landscape, the EU has introduced the Critical Raw Materials Act, aiming to, by 2030, reduce reliance on any single country as a primary source of certain raw materials (seeking less than 65% at any stage of the processing from any single country, having at least 10% of European consumption from domestic extraction). More importantly, the Union's recycling capacity should be able to produce at least 15% of the Union's annual consumption of strategic raw materials (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs 2023). Strategies such as boosting domestic production and diversifying the supply chain are perceived as potential solutions to enhance Europe's autonomy concerning raw materials. Among these initiatives, the AGEMERA project, funded through Horizon Europe, focuses on refining mineral system models, creating innovative tools for studying mineral exploration and mining perceptions, assisting SMEs in their mineral exploration technology development, and promoting awareness of this twin transition (Holma et al. 2022, 2023, Holma 2023).

THE PROJECT GOALS

The project encompasses several key objectives and intermediary outcomes to advance our understanding of geological and mineralogical processes while introducing innovative methodologies. AGEMERA's geological objectives are designed to enhance the understanding and exploration of CRMs through a systematic approach encompassing literature review, field data collection, data synthesis, computer-based modelling, and mineral system model development. The project examines not only surface geology but also the entire crust and upper mantle, with a focus on structures influencing mineralisation. A key strategy involves gathering new field data to fill gaps in geochemical and mineral-chemistry information. This refines computer models to understand CRM distribution in chosen countries better. By combining all data, AGEMERA seeks to provide insights into the location and reasons behind CRM occurrence, identifying previously overlooked areas for exploration. The ultimate aim is to contribute significantly to sustainable mining in the EU.

From the technological side, the project focuses on novel, non-invasive mineral exploration techniques that are environmentally and socially responsible. To this end, the project develops inventive methodologies that embrace innovation and sustainability. These methodologies encompass muography, microseismical surveys, and drone-based electromagnetic surveying. Each approach holds promise in offering insights into subsurface mineral deposits without resorting to intrusive practices.

The project's success hinges on creating a comprehensive data platform. This platform, powered by the AGEMERA AI engine, utilises Artificial Intelligence Knowledge Packs (AI KPs). These AI KPs work through the AGEMERA AI platform's backend to process different data types, such as satellite images, mineral exploration data and mining-related information. They manage tasks like cleaning up data, improving images, and conducting AI-driven analyses. This technology allows closing in on specific regions of interest and gathering customer and satellite data to provide valuable insights about trial mining sites in different countries.

Once published, the user-friendly AGEMERA AI GUI, based on natural language, is accessible on the cloud for easy utilisation.

In tandem with technical advancements, the AGEMERA project acknowledges the pivotal role of a social license to operate (SLO) and social acceptance (SA) within mineral exploration and mining. The project emphasises understanding local contexts, as highlighted by Jason Prno (Prno 2013). To address this, the University of Lapland and its partners designed an online questionnaire piloted in Northern Finland during Q1 of 2023, exploring how diverse operating practices and local conditions impact the mineral industry's acceptability on both local and societal scales. After analysing and adapting the key learnings, the survey will be conducted across AGEMERA partners' research areas in various countries in 2023–2024.

Beyond the scientific and societal dimensions, the project looks into the importance of raw materials to our society, economy, and individual lives. The project promotes responsible resource management, consumption and recycling by enhancing awareness of CRMs' role in our day-to-day existence. These subjects will be addressed through courses at higher educational institutions, public events, and, later in the project, through developing a serious game focused on CRMs and their role in modern society. The project advocates for utilising the United Nations Framework Classification (UNFC) and the United Nations Resource Management System (UNRMS) as pivotal tools for guiding future experts in the field. This integration of international frameworks underscores the project's commitment to aligning its objectives with broader sustainable development initiatives. (United Nations Economic Commission for Europe 2021, Hokka et al. 2020)

THE STUDY AREAS

The project's selected study areas are variably studied using conventional field geological and laboratory methods, novel technologies developed and applied in the project, or combining both approaches. All sites were selected either for their confirmed presence of CRMs or their potential to contain them. The chosen locations capture the breadth of the mining lifecycle by presenting three early-stage projects (one in each in Finland, Spain and Zambia), five current mining sites (one in each in Bosnia-Herzegovina, Bulgaria, Poland and Spain) and two historical mining sites (in Germany). Some of these locations are also studied by applying SLO and SLE research techniques. Geologically speaking, the areas range from the Early Proterozoic Peräpohja belt in Finland to much younger geological terranes (e.g., the Panagyurishte region of the Apuseni-Banat-Timok-Srednogorie belt in Bulgaria; (Peytcheva et al. 2022)).

The deposits in the selected study areas fall into a diverse range of genetic types: 1) orogenic gold enriched in cobalt in Finland; 2) stratabound copper and silver enriched in cobalt, zinc, nickel, molybdenum and vanadium in Poland; 3) karst bauxite in Bosnia-Herzegovina; 4) porphyry copper and epithermal gold in Bulgaria, locally associated with platinum group elements; 5) volcanogenic massive sulphide deposits, characterised by nickel-copper-cobalt, in Spain; 6) lithium and tin greisens in Germany; and 7) sedimentary rock-hosted manganese in Zambia. In addition, the geological team has also reviewed the possibilities of studying metasomatically enriched lithium mineralisation in Spain and poorly outcropping iron oxide copper gold mineralisation in Bulgaria. Among the most notable deposits studied in the project are the Assarel open-pit porphyry copper mine and the Lubin underground Kupferschiefer-type copper mine. Regarding the

technologies to be developed in AGEMERA, passive seismic methods are applied in Bosnia-Herzegovina, Spain and Poland, airborne fixed-wing drone geophysics (UAV EM) in Finland and Zambia, and muography in Poland, Bosnia-Herzegovina and Bulgaria.

THE CURRENT STATUS OF THE AGEMERA PROJECT

The AGEMERA project has completed approximately one year of its three-year duration. Novel technologies have been successfully deployed in various trial areas, marking a significant step forward. The introduction of initial university courses, integrated into existing curricula, has already taken place, while the development of new courses is actively underway. A pivotal pilot questionnaire, utilising a softGIS approach, has been launched to gauge public perceptions, aspirations, and concerns regarding mineral exploration and mining, particularly in regions of personal significance. The ongoing analysis of the questionnaire responses is providing valuable insights. AGEMERA AI has showcased its prowess in seamlessly integrating diverse datasets, encompassing the outputs of the novel technologies developed within the project.

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REFERENCES

European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs 2023. Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) 168/2013, (EU) 2018/858, 2018/1724 and (EU) 2019/1020. Available at: https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:52023PC0160

Grohol, M. & Veeh, C. 2023. Study on the Critical Raw Materials for the EU 2023 – Final Report. Publications Office of the European Union. Available at: https://doi.org/10.2873/725585

Hokka, J., Eilu, P., Ahtola, T., Kivinen, M., Konnunaho, J., Kuusela, J., Lintinen, P. & Törmänen, T. 2020. Application of the UNFC Resource Code in Finland Practical Guidelines. Signature 50403, 30115.

Holma, M. 2023. AGEMERA: Fuelling a Greener Economy via Innovative Mineral Exploration. EU SuperCluster Lapland Geoconference, 30–31 October, 2023, Rovaniemi, Finland. 1 p.

Holma, M., Korteniemi, J., Casini, G., Saura, E., Šumanovac, F., Kapuralić, J. & Tornos, F. 2022. Agile Exploration and Geo-modelling for European Critical Raw Materials – Introduction to the AGEMERA project. Institute of Seismology, University of Helsinki, Report S-72, 51–54.

Holma, M., Peytcheva, I., Šumanovac, F., Tornos, F., Nyambe, I. & Joutsenvaara, J. 2023. Horizon Europe project AGEMERA: Combining novel methodologies for agile exploration and geomodelling of critical raw materials deposits. Proceedings of the Geological Society of Finland, Vol. 3, Abstracts of the 1st GeoDays 14th–17th March 2023. Helsinki: The Geological Society of Finland. University of Helsinki, p. 43. Available at: http://hdl.handle.net/10138/357482

Muench, S., Stoermer, E., Jensen, K., Asikainen, T., Salvi, M. & Scapolo, F. 2022. "Towards a Green & Digital Future." 10.2760/54 (print). Luxembourg: Publications Office of the European Union. Available at: https://doi.org/10.2760/977331

Peytcheva, I., Hikov, A., Georgiev, S., Stefanova, E., Dimitrova, D., Ivanov, D., Stoilov, V., Vasilev, I. & Holma, M. 2022. Combining agile exploration methods with mineral chemistry for better geo-modeling of critical raw materials in the Assarel porphyry copper deposit. In: Peytcheva, I., Lazarova, A., Granchovski, G., Ivanova, R., Lakova, I. & Metodiev, L. (eds) XXII International Congress of the CBGA, Plovdiv, Bulgaria, 7–11 September 2022, Abstracts. Geologica Balcanica, Geological Institute, Bulgarian Academy of Sciences, p. 348.

Prno, J. 2013. An Analysis of Factors Leading to the Establishment of a Social Licence to Operate in the Mining Industry. Resources Policy 38(4), 577–590. Available at: https://doi.org/10.1016/J.RESOURPOL.2013.09.010

United Nations Economic Commission for Europe 2021. United Nations Resource Management System: An Overview of Concepts, Objectives and Requirements. ECE Energy Series 68. Available at: https://unece.org/sites/default/files/2021-05/2017886_E_ECE_ENERGY_134_WEB.pdf

PROJECT BATTRACE – USING GEO-BASED FINGERPRINTING FOR BATTERY RAW MATERIAL TRACEABILITY

by

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Traceability serves as a vital tool for enhancing transparency along the supply chain of battery raw materials. Ideally, traceability of raw materials would not be required if there existed a global trust that all mining companies operated in a socially, environmentally, and economically sustainable manner. The establishment of sustainability and responsibility standards should, in theory, guarantee transparency and trust throughout the mining supply chains.

Nonetheless, with the anticipated exponential growth in global demand for battery minerals, this increased demand may create financial incentives for certain companies or entities with subpar performance to adopt unsustainable business practices. The technological capability to trace the origins of raw materials to their geographical source can serve as a deterrent against any attempts by actors to falsely claim the origins of their raw materials.

BATTRACE represents a research initiative in which the Geological Survey of Finland has been pioneering an innovative approach to battery mineral traceability known as geo-based fingerprinting. In this method, a material's origin can be traced back to its initial source based on specific material characteristics, such as its mineralogical and elemental compositions.

Numerous ongoing initiatives are currently underway to integrate traceability into battery mineral supply chains. Geo-based fingerprinting holds the potential to serve as a traceability method for multiple raw materials utilized in batteries. Given that the geological and elemental attributes of a sample cannot be altered, the geo-based fingerprinting method developed within BATTRACE possesses a unique capacity to function as a standalone traceability technology or as a supplementary verification method alongside other traceability systems.

AUTHORS' NOTES

The general topic of the project has been shortly introduced by invitation in an oral presentation at the EU Raw material week in November of 2021 and as a research poster in SEG2023 conference in August of 2023.

In addition, the project has produced a research report, which includes some information of the project and methodology (report available at: https://tupa.gtk.fi/raportti/arkisto/20_2022.pdf).

CODA BASED APPROACH TO SURFICIAL AND TILL GEOCHEMISTRY

by

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Compositional data (CoDa) are the data that can be summed up to a fixed constant (e.g., percentages, proportions) and these data contains the ratios between measured components that represent relative information between measurements (Filzmoser et al. 2018). Geochemical data is also considered as compositional data and targeting till, regional till and rock geochemical datasets of Finland are the three main datasets that are going to be considered in this abstract. The targeting till geochemical data set contains around 385 000 soil samples collected by the Geological Survey of Finland (GTK) along sample lines in certain areas between the years from 1971 to 1983. The point density of the samples lies between 6–12 samples per km^2. An emission quantometer method has been used to measure the concentration of 17 elements (Gustavsson et al. 1979). The other till geochemical data set is the regional till data which cover whole Finland and has been collected during 1983 to 1991. This data set contains the concentrations of 22–26 elements (depending on the map sheet) and the sampling density is one sample per 4 km^2 including the full data set of 82 062 samples (Salminen & Tarvainen 1995). The rock geochemical dataset contains the concentrations of different elements in Finnish bedrock for 6544 samples. The sampling has been done between 1990 and 1995 and the sampling density differs between one sample per 30–120 km^2 (Geological Survey of Finland 2007).

In this abstract, a subset of data from the Central Lapland area, Finland (Fig. 1) has been considered. The selected subset of the regional till data generally has good data quality. However, for some elements it contains values below the lower detection limit, and some special symbols associated with specific data quality issues whereas rock geochemical dataset was associated with some values below the lower detection limit. Therefore, additional data cleaning was required. Compared to the previous data sets, the targeting till geochemical data set has serious data quality issues, typically connected to values related to detection limits, zeros and even negative analytical results, and values marked with special symbols. Therefore, extensive data cleaning was required.

Q-Q plots are used to evaluate the distribution of concentrations between different map sheets in the regional as well as in the targeting till data sets to analyse the mismatch between map sheets (Fig. 2). The Q-Q plots vary quite strongly

between map sheets M4, M5, M11, M12 (Fig. 1) for the element Ni, as well as between targeting and regional till data sets despite compositional transformation. The variation of Q-Q plots between map sheets might be either a result of levelling problems between map sheets or the distribution of the Ni concentration may change across the map sheets. Thus, it was decided not to combine the values from the map sheets in the analysis, but to analyse the map sheets (1:100 000 scale) separately, as the small areas contain enough sample points to carry out the analysis. However, the differences between the two data sets might be mainly due to different analytical techniques as targeting till data is based on total analytical method and regional till data is based on partial leaching (i.e. aqua regia) method.

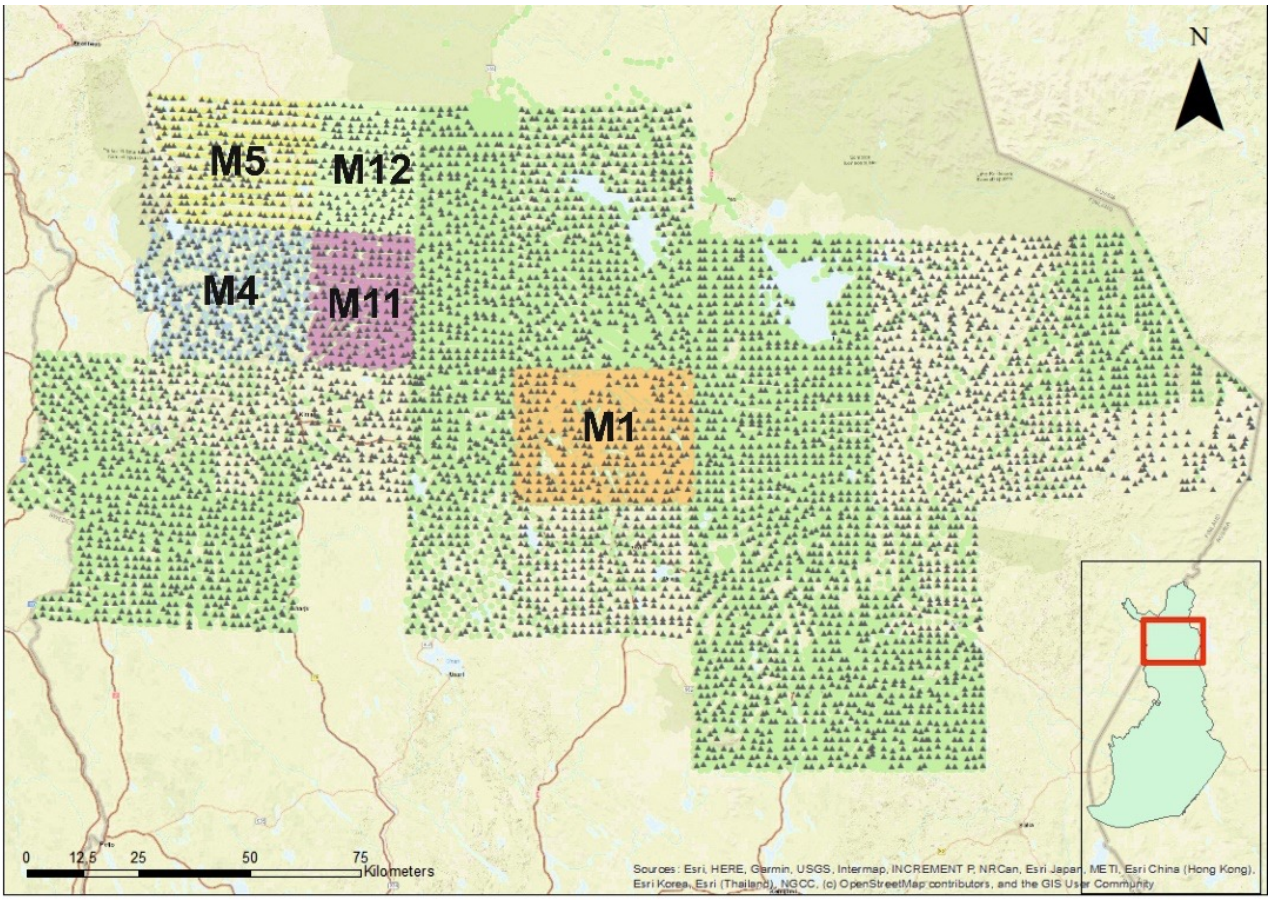

Fig. 1. Study area in Finland (regional till data points are marked in grey color triangles, targeting till data points are marked in green color dots) and M1, M4, M5, M11, M12 map sheets.

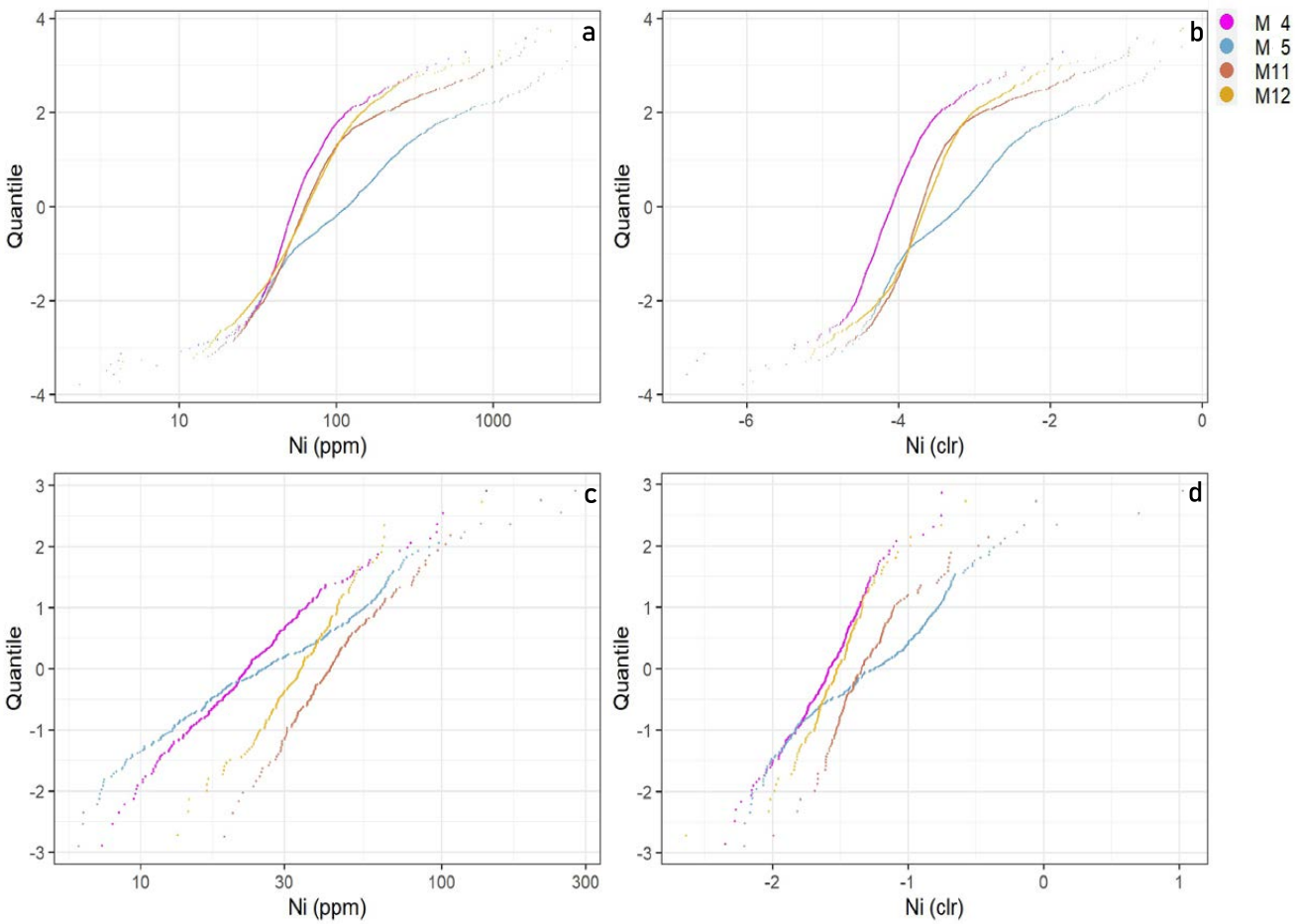

Fig. 2. Q-Q plots of Ni: a) original concentration in targeting till, b) clr transformed concentration in targeting till, c) original concentration in regional till, d) clr transformed concentration in regional till, n (line till) = 16460, n (regional till) = 870.

PCA maps were generated for the selected area (M1) which contains two Ni-Cu-PGE deposits (Sakatti and Kevitsa – Fig. 3), by considering all 3 data sets separately. The intention was to understand the link between underlying geology and geochemical analyses results. According to PCAs, the 3 data sets indicate three different relationships between Ni and Cu for the same area M1. The reason for having different correlation for Ni and Cu between targeting and regional till data sets is not clear, as the same till material has been used in two datasets except for the analysis method. However, the loadings for Cu are lower in both targeting and regional till data sets whereas it is higher in the weathered bedrock PCA, which could indicate some sort of deficiency in releasing Cu containing minerals to the till. In lithogeochemical data set, there are few data points (23) that have been collected from weathered bedrock and the sampling points are sparse. This may cause a lack of correlation between Ni and Cu in the weathered bedrock PCA. Thus, it may show an entirely different correlation with Ni and Cu than in till. In all three plots Ti, V and Al positively correlate with each other.

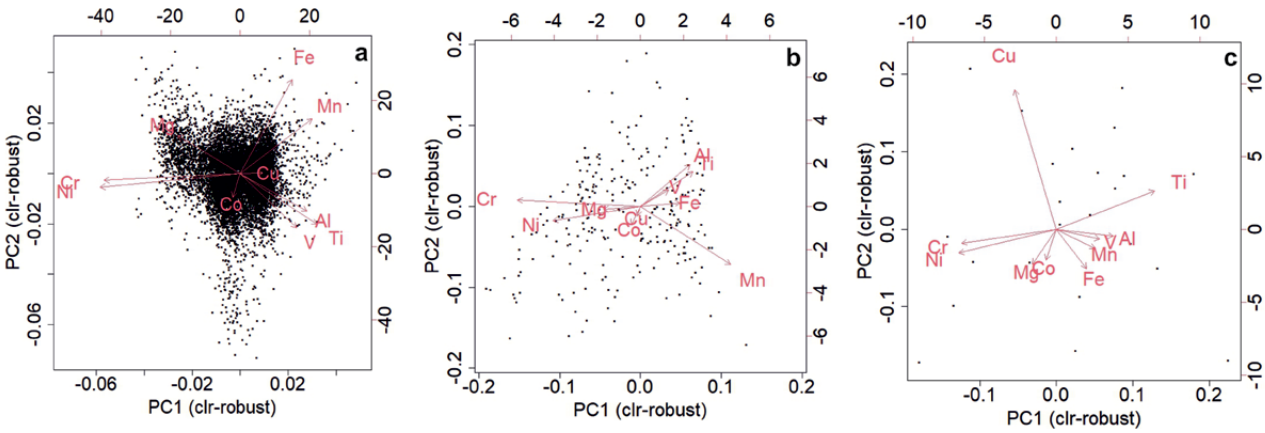

Fig. 3. PCAs of selected area M1 a) targeting till b) regional till c) weathered bedrock.

Another approach in surficial geochemistry is to test how upper soil weak leach geochemical methods and biogeochemistry is working in tracing the critical metal sources in different soil types and landuse areas in Europe. The target areas locate in Czech Republic, Finland, Poland and Portugal. Aims are to test if the deposit is detectable at the surface, influence of the bedrock lithology, and the influence of surface cover on the geochemical signal on thick sediment cover such as a top of esker and typical till cover.

The first testing of surficial geochemical exploration methods was carried out in July 2022 at the Akanvaara test site (V-Cr-PGE layered intrusion) in Finland. The test includes both upper soil and plant sampling from 86 sampling stations which were chosen over the known layered intrusion at the boreal forest environment. For the soil analyses samples were collected from Ah, B and C horizons of the Podsol-type soil, and for the plant analyses different plant materials such as Common juniper twigs and needles, Labrador tea twigs, Norway spruce twigs and needles, Norway spruce bark as well as Pinecones were used.

Preliminary exploratory data suggest that Ni behaves same manner with Co, Cd and less with Cu. Thus, preliminary results may show a significant response to many elements with known mineralised bedrock targets observed in the drill core data. As an example, Cu and Ni concentrations by the Ionic leach analytical methods in the upper soil samples is presented in Figure 4. Elemental distribution is also reflecting the lithological variations of the rock units in the bedrock. Based on the results, it is obvious that a) there is good or moderate correlation for several elements between the surface geochemical data and underlying bedrock, and b) soil analysis method using certain soil sampling procedure and selective extraction is an effective, environmentally friendly geochemical exploration technique in the glaciated terrains. However, later during this project statistical models based on the principles of compositional data analysis (CoDa-principle) will be used to analyse these multi-variate and multi-parameter data sets for the major factors for element cycling between soil and plants.

Fig. 4. Cu and Ni distribution in the Ionic leach results of Akanvaara area.

REFERENCES

Filzmoser, P., Hron, K. & Templ, M. 2018. Applied compositional data analysis. Cham: Springer.

Geological Survey of Finland 2007. Rock geochemical data of Finland. Available at: https://tupa.gtk.fi/paikkatieto/meta/rock_geochemical_data_of_finland.html. [Accessed 22.8.2023]

Gustavsson, N., Noras, P. & Tanskanen, H. 1979. Seloste geokemiallisen kartoituksen tutkimusmenetelmistä. Summary: Report on Geochemical mapping methods. Geological Survey of Finland, Report of Investigation 39. 20 p. Available at: https://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_039.pdf

Salminen, R. & Tarvainen, T. 1995. Geochemical mapping and databases in Finland. Journal of Geochemical Exploration 55 (1–3), 321–327.

PUBLIC COMMUNICATIONS PROJECT TO SUPPORT PRIVATE EXPLORATION

by

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Siikalatva municipality set up a year-long communications project to support graphite exploration in the region. The aim of the project is divided into three main objectives:

1. Delivering information about exploration and mining for residents of Siikalatva and the landowners in the exploration project area
2. Hearing the stakeholders' opinions on exploration and mining and delivering them to Siikalatva municipality.
3. Educating Siikalatva municipality officials and local politicians about their rights and obligations regarding exploration and mining, especially because Finland has new mining and nature conservation legislation effective from 1st of June 2023.

To achieve these three goals, one seminar has been organised so far with speakers from public organisations GTK (Geological Survey of Finland), TUKES (Finnish Safety and Chemicals Agency) which is the mining authority in Finland. Also, CEO of Suomen Malmitutkimus Oy, the exploration company, was presenting their project. The communications project manager has also taken part in local summer events conducting a resident survey about exploration and possible mining in the region.

One lecture at local high school was conducted about materials and their demand in modern society. Students were very receptive to hearing about it. It is important to reach out to young people also, they will be adults at the time when the exploration project possibly succeeds and turns into mining.

Soon, 3 more public seminars will be held. One about local geology, one about environmental impacts of mining and one about local services needed by exploration companies. The latter one is aimed for local entrepreneurs. The plan is to get good quality speakers for all these seminars.

Preparations for education package for local politicians and administrators are also underway. Website for communications has been made available for local people, where maps and general information is shared. Cooperation with Siikalatva municipality personnel has been key to reaching the people.

This communications project is executed by Haapavesi-Siikalatva regional development organisation (Haapaveden-Siikalatvan seutukunnan kuntayhtymä),

which is a public organisation owned by municipalities of Haapavesi, Siikalatva and Pyhäntä in Southern Oulu region. The project funding comes from Council of Oulu region (Pohjois-Pohjanmaan Liitto) and Siikalatva municipality. Funding comes from national sources (AKKE), not from EU.

DATING AND TRACE ELEMENT CHARACTERISATION OF SN-W SKARN-, GREISEN- AND VEIN-TYPE OCCURRENCES FROM EAST GREENLAND

by

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The traceability of Sn- and W-minerals to their deposit type (skarn, greisen or hydrothermal veins) was tested on rock samples and stream sediments from East Greenland. Scheelite and cassiterite grains from nine occurrences were analysed for their host rock mineral assemblage and geochemical fingerprint (trace elements and dates by laser-ablation inductively coupled plasma mass spectrometry). Samples from ten localities were collected from skarn, greisen or metamorphic vein occurrences. The mineralogy of the samples was investigated with automated quantitative mineralogy (AQM) and trace elements of minerals from these outcrops were compared to trace element values for the same deposit types in literature. Furthermore, U/Pb-dating of the scheelite, cassiterite as well as zircon, apatite and rutile formed during the same mineralising events were estimated, to determine the timing of the mineralisation. AQM observations on the thin sections match well with trace element data, while new dates of the minerals reveal a more complex mineralisation history than previously known, with seemingly comprising at least three pulses during the Caledonian orogeny.

Tin (Sn) and especially tungsten (W) occurrences in East Greenland were extensively studied by the exploration company Nordisk Mineselskab A/S from the late 1960s to early 1980s, sporadically followed up by investigations by GEUS and the Greenlandic Ministry of Mineral Resources (MMR) in the forty years afterwards, latest during the Summer 2022. Most of the occurrences are connected to the Caledonian orogeny in East-Greenland (Fig. 1). Mineral occurrences are found in the uppermost Caledonian thrust sheet and in the passively overlying sediments of the Franz Joseph allochthon and are thought to be associated with the intrusion of Silurian and Devonian S-type granites (Higgins et al. 2004). Sn-mineralisation is observed as cassiterite, while W is found in scheelite. Mineralised rocks are found as skarn, greisen or quartz-scheelite vein occurrences, depending on their host rock and the proximity to granites (Hallenstein & Pedersen 1982).

Literature data reveal that different deposit types, like skarns, greisen, and metamorphic vein-type each have their own set of mineral trace element compositions (e.g., Wang et al. 2022, Sciuba et al. 2020 and many others). A good understanding of elemental variations can serve in assessing the potential for

what deposit types are expected to be found upstream based on analysed stream sediment or till samples.

The occurrences in East Greenland can be divided into three major groups (Hallenstein & Pedersen 1982): 1) Skarn deposits related to the formation of thin granitic sheets in high-grade metamorphic sediments of the Krummedal sequence in the Hagar Bjerg thrust sheet. These are all scheelite occurrences; 2) Greisen deposits related to magmatic fluids and large granitic bodies intruding into the lower Eleonore Bay Supergroup of the Franz Joseph allochthon. Both cassiterite and scheelite occur; 3) Metamorphic quartz-scheelite veins, associated with antimony, arsenic, and copper found in bituminous limestone beds of the upper part of the Eleonore Bay Supergroup. Samples from ten different localities in East Greenland were investigated (Fig. 1).

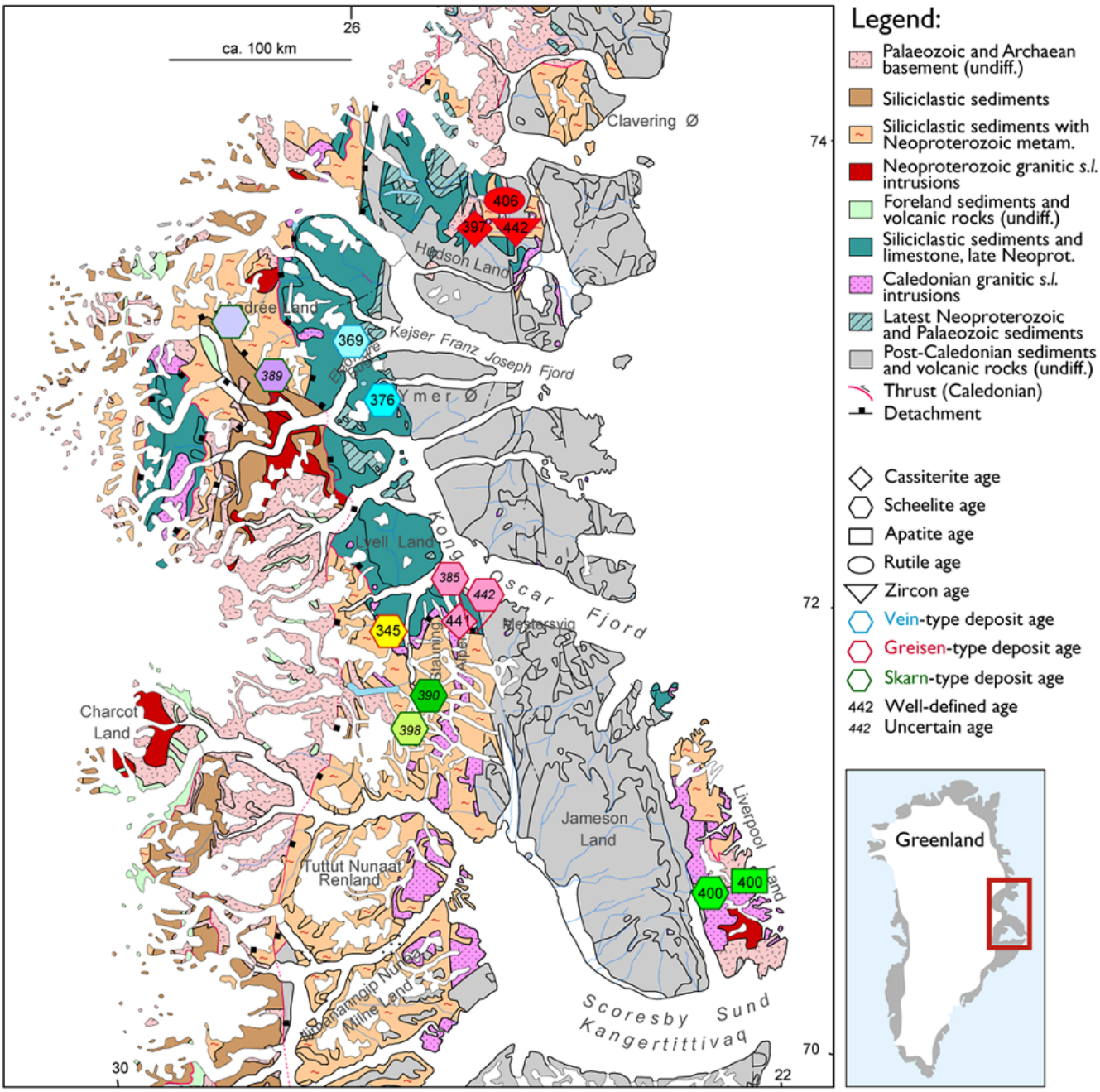

Fig. 1. Map of East Greenland showing the major known scheelite and cassiterite localities. Occurrences were dated with U/Pb isotopes on scheelite, cassiterite, zircon, apatite and rutile. Ages indicated on the map. Map modified from GEUS G2.5M map.

Thin sections of samples were investigated with AQM to study the mineral assemblage formed during the mineralisation. AQM is a scanning electron microscope technique that combines back-scattered electron imaging with chemical analyses by energy dispersive spectroscopy in a mosaic with a small step-size (Keulen et al. 2020). Each analysis is interpreted as a mineral species and is coloured as a pixel in the false-coloured mineral map. Furthermore, cathodoluminescence (CL) imaging is performed to study growth zonation within scheelite and cassiterite.

Laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) analyses were performed with two purposes: **1)** to investigate the age constraints of mineralisation of scheelite, cassiterite together with other minerals formed at the same time, and **2)** to characterise the deposit type by estimating the characteristic range of trace elements in its minerals. For this second purpose a database of literature data for cassiterite (K. Foltyn), scheelite and tourmaline was built. To facilitate the matrix-matched cassiterite dating by LA-ICP:MS, a new standard was developed (Thomsen et al., in prep.).

AQM observations confirm the three main settings with skarn, greisen and metamorphic vein occurrences (Fig. 2), but also reveal differences in the mineral assemblages from the individual occurrences depending on the composition of the host rock, metamorphic conditions during mineralisation and variations in the metasomatic fluids.

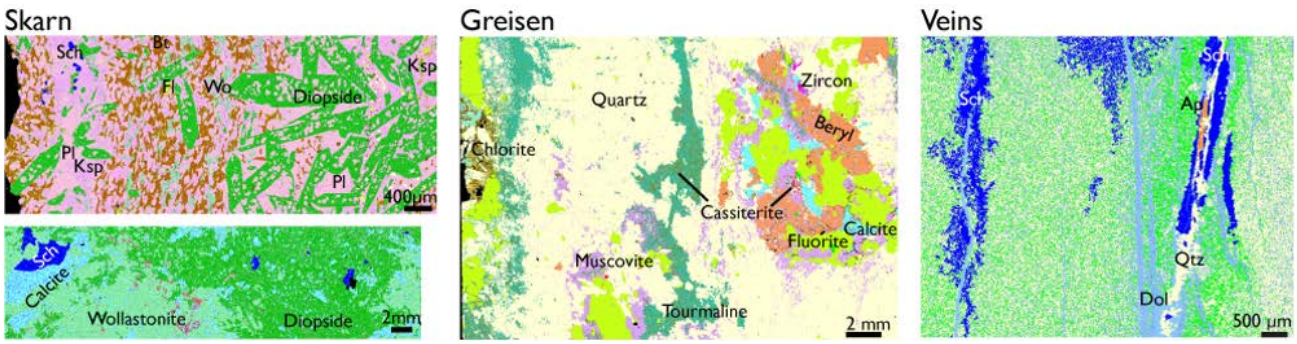

Fig. 2. Examples of mineral assemblages observed in skarn, greisen and vein-type occurrences. AQM maps.

ICP-MS analyses showed that the mineralisation of Sn and W did not occur in a single event but consisted of at least three different pulses likely between 441–369 Ma (Fig. 1). This indicates that the mineralisation was triggered by local events, rather than a single regional event and that the timeslot with optimal conditions for melting and fractionation was longer than previously assumed. Comparison of the trace elements reveals that the scheelite and cassiterite occurrences from the study area compare well to literature trace element data and that skarn, greisen and orogenic vein-type deposits can be distinguished from each other with multivariate statistics (Fig. 3).

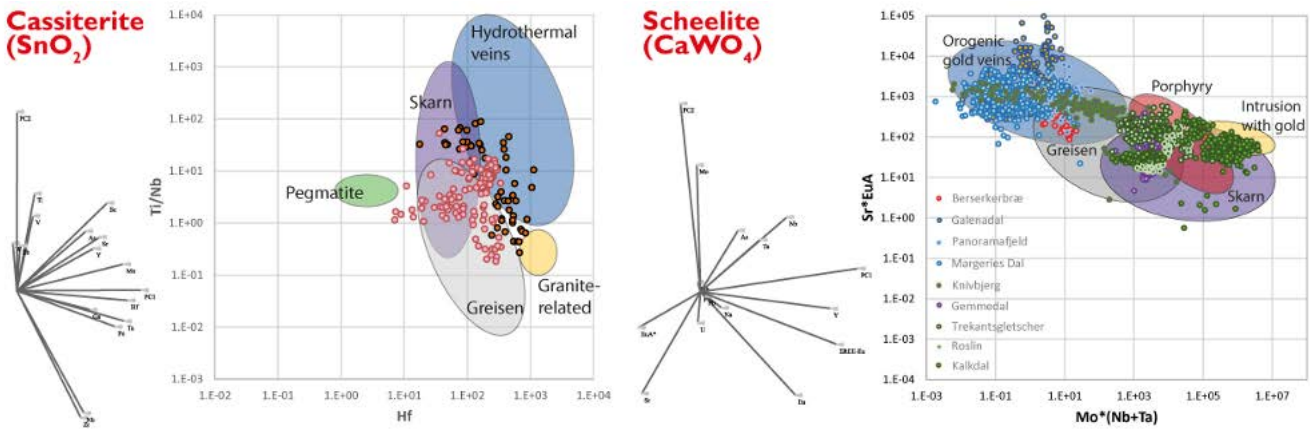

Fig. 3. Principal component analyses based on literature data for cassiterite and scheelite. 2D visualisation for some distinctive trace elements, where literature data is plotted in circles per deposit type and the Greenlandic data is shown as individual analyses per sample locality.

Formation of scheelite and cassiterite was possible during at least three stages in the history of the area: The first pulse at ca. 445–441 Ma was observed as the dates of cassiterite in Berserkerbræ. This age is not well understood, as it is older than the Caledonian S-type granites. Migmatisation was reported in the metasedimentary rocks of the Hagar Bjerg thrust sheets from 446 Ma onwards (Gilotti & McClelland 2008). This might have caused a local fractionated melt, resulting in enrichment in Sn (and W) and the formation of greisen with cassiterite.

Most S-type granites were emplaced near 425 Ma (Kalsbeek et al. 2008). S-type granites are typically the source of Sn and W in occurrences. McClelland and Gilotti (2003) define this period as the first stage of synorogenic extension, thus transporting heat to the Krummedal metasediments, which will likely promote partial melting and fractionation of Sn and W in the magma.

During the main pulse of mineralisation both scheelite and apatite from Kalkdal, as well as cassiterite and rutile from Blokadedal all give the same date (ca. 403 Ma), which possibly is the age of chemically evolved Devonian granites in area (Steenfelt 1982). AQM observations reveal that rutile and apatite formed as part of the mineralisation process and most likely were absent before the mineralisation. Therefore, it is speculated that a renewed fractionation occurred, which produced granitic magma enriched in tin and tungsten. McClelland & Gilotti (2003) associated an age of 404 Ma with late orogenic extension and exhumation, which is a possible explanation for this renewed fractionation.

The last pulse of mineralisation is observed in vein-type occurrences, including Margeries Dal area and is significantly younger (ca. 376–369 Ma). These scheelite occurrences, are not spatially associated with a granite, which agrees with the trace element signature in tourmaline and scheelite from the same occurrences.

Integration of absolute dating and trace element compositions on the scheelite and cassiterite occurrences in the area lead to a better understanding of the different mineralisation styles. Furthermore, the methodologies presented here act as a platform serving to improve our understanding of the geological processes relevant for the formation of cassiterite and scheelite deposits in East Greenland.

The project was financed by GEUS, EIT-RM project MinExTarget #109674 and the Greenlandic Ministry of Mineral Resources, Government of Greenland. Geologists from Nordisk Mineselskab A/S are thanked for collecting samples. M. Alaei and H. Vesturklett are thanked for laboratory assistance. K. Foltyn is thanked for collecting cassiterite trace element data from literature.

REFERENCES

Gilotti, J. A. & McClelland, W. C. 2008. Geometry, kinematics, and timing of extensional faulting in the Greenlandic Caledonides – A synthesis. In: Higgins, A. K., Gilotti, J. A. & Smith, M. P. (eds) The Greenland Caledonides – evolution of the northeast margin of Laurentia. Geol. Society of America, Memoir 202, 251–271.

Hallenstein, C. & Pedersen, J. 1982. Study of Scheelite Mineralization in Central East Greenland. GEUS Dodex file report 20688. Nordisk Mineselskab A/S. 152 p.

Higgins, A., Elvevold, S., Escher, J. C., Frederiksen, K. S., Gilotti, J. A., Henriksen, N., Jepsen, H. F., Jones, K. A., Kalsbeek, F., Kinny, P. D., Leslie, A. G., Smith, M. P., Thrane, K. & Watt, G. R. 2004. The foreland-propagating thrust architecture of the East Greenland Caledonides 72–75. London: N. J. Geol Soc 1661, 1009–1026.

Kalsbeek, F., Higgins, A. K., Jepsen, H. F., Frei, R. & Nutman, A. P. 2008. Granites and granites in the East Greenland Caledonides. In: Higgins, A. K., Gilotti, J. A. & Smith, M. P. (eds) The Greenland Caledonides – evolution of the northeast margin of Laurentia. Geol Soc Am Mem 202, 227–249.

Keulen N., Malkki S. N. & Graham S. 2020. Automated Quantitative Mineralogy Applied to Metamorphic Rocks. Minerals 10(1), 47. 29 p. doi:10.3390/min10010047

McClelland, W. C. & Gilotti, J. A. 2003. Late-stage extensional exhumation of high-pressure granulites in the Greenland Caledonides. Geology 31, 259–262

Sciuba, M., Beaudoin, G., Grzela, D. & Makvandi, S. 2020. Trace element composition of scheelite in orogenic gold deposits. Mineral Dep 55, 1149–1172.

Steenfelt, A. 1982. Uranium and selected trace elements in granites from the Caledonides of East Greenland. Mineral Mag 46, 201–210.

Wang, C., Zhao, K., Chen, J. & Ma, X. 2022. Examining fingerprint trace elements in cassiterite: Implications for primary tin deposit exploration. Ore Geology Reviews 149, 105082. 13 p.

MULTIMINER – MULTI-SOURCE AND MULTI-SCALE EARTH OBSERVATION AND NOVEL MACHINE LEARNING METHODS FOR MINERAL EXPLORATION AND MINE SITE MONITORING

by

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The Multi-source and Multi-scale Earth observation and Novel Machine Learning Methods for Mineral Exploration and Mine Site Monitoring (MultiMiner) project is a Research and Innovation Action (RIA) project funded from the Horizon Europe programme in years 2023–2036. The goal of the project is to develop novel data processing algorithms for cost-effective utilisation of Earth Observation (EO) technologies for mineral exploration and mine site monitoring (Fig. 1). The purpose is to further unlock the potential of EO data, including Copernicus, commercial satellites, upcoming missions, airborne and low altitude as well as *in situ* data. Solutions are created for all stages of the mining life cycle including mineral exploration, operational, closure and post-closure stages. The core idea of the MultiMiner project is to create innovative machine learning solutions which do not require any or only little *in situ* reference data. The project focuses on new EO based exploration technologies for critical raw materials (CRM) to increase the probability of finding new sources within EU thereby strengthening the EU autonomy in the area of raw materials. MultiMiner EO based exploration solutions have extremely low environmental impact, and are thus socially acceptable, economically efficient and improve safety. The project's solutions for mine site monitoring increase the transparency of mining operations as environmental impacts can be detected as early as possible and digital information of the currently unexploitable raw materials can be stored for future generations. The applicability of the developed algorithms is demonstrated in five European test sites (Fig. 2). The core scientific work in the project is divided into three work packages where the first two develop algorithms for mineral exploration and mine site monitoring, and the third one demonstrates their applicability and accuracy in real mining and exploration environments of critical and strategic raw materials.

Work package 2, **Multi-source and multi-scale mineral prospectivity EO mapping**, develops scalable and automated approaches for mineral exploration based on multi-source EO data and sparse *in situ* data. The focus is on mineral deposits hosting CRMs. Firstly, a novel mineral mapping algorithm performing automatic spectral feature extraction from a comprehensive mineral spectral library is developed. This algorithm will significantly improve accuracy and time-efficiency of direct mineral identification of CRMs and other raw materials based on EO data. Secondly, we implement workflows for multi-scale EO data interpretation, to produce value adding mineral maps for local to regional scale exploration. Thirdly, a mineral prospectivity wizard, facilitating multi-scale mineral mapping and automatic interpretation for non-experts, is coded and tested.

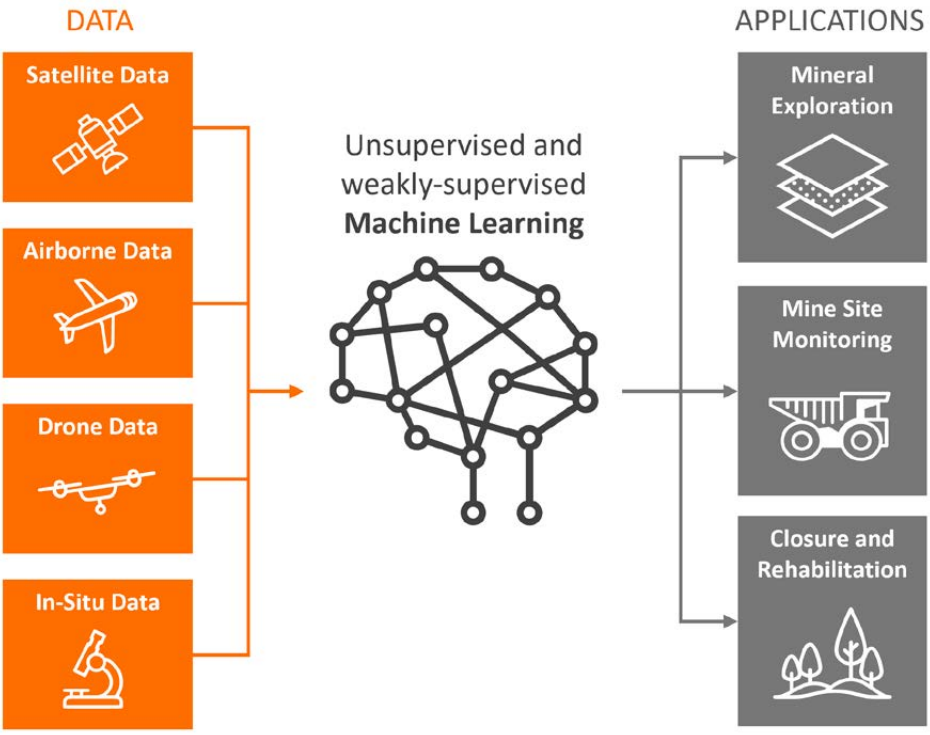

Fig. 1. MultiMiner project takes advantage of recent space- and airborne EO technologies and harnesses them for the use of mining industry by creating efficient unsupervised and weakly-supervised data analysis algorithms which require limited in situ data.

In work package 3, **Timely mine site monitoring**, novel EO data analysis methods are designed and developed to make use of the scarcely available *in situ* data for timely mine site monitoring. The larger goal is to reduce both disruptions to mining activities and environmental impacts. The objectives are 1) to develop a novel generic mine site monitoring algorithm, capable of combining multi-source EO data at various temporal, spatial and spectral resolutions, and requiring only a limited amount of *in situ* data, 2) to adapt and fine tune the generic algorithm to automatically monitor impacts to the environment, including water quality, acid mine drainage, dust and revegetation, and 3) to develop an integrated 3D tailings storage facility monitoring method, capable of jointly monitoring tailings composition and volume, as well as ground stability of tailings dams and open pit walls.

Finally, work package 4, **Site demonstrations**, showcases the novel exploration and monitoring methods developed in work packages 2 and 3. The demonstrations are conducted in four active mining sites, namely Hochfilzen, Austria (RHI Magnesita) and Olympias and Stratoni, Greece (Hellas Gold) and Ihalainen, Finland

(Nordlkalk Oy, Fig. 2). Magnesium, as a CRM, is quarried at the Weissenstein mine in Hochfilzen. In the Chalkidiki region, where Olympias Au-Ag-Pb-Zn and Stratoni Ag-Pb-Zn mines are located, CRMs Ga and Sb are hosted in the Olympias deposit. At the Chalkidiki area, a high-grade Au-Cu Skouries development project is also located, which contains locally elevated concentrations of Platinum Group Metals and Bi, both CRMs in the 2020 CRM list by the EC. At Hochfilzen, the mineral mapping algorithms are tested in constrained conditions at the Weissenstein mine and further applied for a real exploration case on a regional scale. Kallyntiri test site in Greece, highly prospective for Sb, and Chalkidiki also serve as case studies for regional exploration demonstrations. Besides Weissenstein, Kirki, an abandoned mine in Greece, and Ihalainen serve the purposes of testing the environmental monitoring, tailings storage facility monitoring as well as ground stability monitoring approaches.

Besides demonstrating the added value of novel mineral prospectivity products and the novel timely mine site monitoring products, WP 4 also aims to implement strategies to reduce *in situ* data collection needs. Statistically sound thematic accuracy assessment methods are selected based on a literature review and applied to assess the accuracy of the developed data analysis methods. The aim is also to improve *in situ* data standardisation and harmonisation specific for mineral exploration and mine site monitoring.

Fig. 2. MultiMiner partners. Mining and exploration test sites Ihalainen limestone quarry (Lappeenranta, Finland), Weissenstein magnesite mine (Hochfilzen, Austria), Kallynthiri public exploration site, Chalkidiki mining area (Olympias and Stratoni mines) and Kirki abandoned mine (Greece) are highlighted with dark grey symbols.

The MultiMiner project follows the open access policy for algorithms, data, their metadata and publications, whenever possible. New unsupervised easy-to-use tools to conduct EO-based mineral exploration and mine site monitoring are made available for further exploitation and development through Github. In the long run the project's solutions for EO-based exploration are expected to lead to potential discoveries of new CRM deposits. In addition, mine site monitoring solutions are expected to increase the transparency of mining operations enabling environmental impacts to be detected as early as possible, and also lead to better mining safety. In that respect, MultiMiner will engage actively with the general public and policy makers to raise the awareness about the project and its objectives, and share its innovative methods with European stakeholders to stimulate further research and developments, and ensure their exploitation by end-users (mining industry, governmental and non-governmental organisations, scientific community, local authorities, etc.).

MultiMiner is a pan-European consortium consisting of 12 partners and 1 associated partner from research institutes, academia, consulting businesses and mining industry with interdisciplinary backgrounds in geology, remote sensing and machine learning (Fig. 2). The members come from six EU member states which represent mining regions across Europe with diverse geology with evident potential for various types of CRM resources. The project is led by Geological Survey of Finland, GTK. For further information follow the project on the project webpage at www.multiminer.eu and at social media channels.

SPATIAL INTERSECTION BETWEEN CRITICAL RAW MATERIAL OCCURRENCES AND PROTECTED AREAS IN EUROPE

by

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INTRODUCTION

Land use issues have been identified as one of the main causes for mining and mineral exploration disputes (Valenta et al. 2019, Lèbre et al. 2020, Owen et al. 2022). The issues can often be related to protected areas (PAs). As part of the CIRAN (CrItical RAw materials extraction in enviroNmentally protected areas) project, a Europe-wide assessment of the spatial intersection between known Critical Raw Material (CRM) occurrences and PAs (e.g. Natura 2000) is done. The objective of the assessment is to understand the potential conflicts of land use in Europe in relation to exploiting CRMs. This is done by spatially analysing the overlap between locations of CRMs and the PAs. The analysis reveals if and how widely CRMs have been found within or near PAs.

The findings of this assessment are the first steps needed to begin assessing how to predict and avoid potential future conflicts that may arise due to differing social objectives between the need for (critical) raw materials and the need to conserve natural and cultural resources represented by the different PAs (Valenta et al. 2019, Lèbre et al. 2020, Owen et al. 2022).

DATA & METHODS

To conduct this assessment, we utilise integrated datasets on raw material occurrences from previous EU projects. Available data on (critical) raw materials (including exploited and only discovered ones) varies widely between countries in Europe. In the EU projects FRAME (Fig. 1) and MINTELL4EU the problem of heterogeneous datasets between countries has been tackled and as a result multiple Europe-wide integrated datasets now exist. However, due to the heterogeneity of the country data the integrated datasets still do not represent each country or area equally. As the reporting by individual countries and the subsequent integrating of the Europe-wide data improves so will the results of this assessment. The data on raw material occurrences is typically point or polygon data with additional attributes defining the exploitation status and size of the material occurrence. This data

will be used, when available and valid, to understand the significance of a single mineralised deposit and consequently use the significance as a weight in analyses. The types of resources that are collected in the datasets not only contain CRMs but also construction rock materials. However, we focus on CRMs, defined by the European Commission, and which include as an example rare earth elements (REE) and platinum group metals (European Commission 2020).

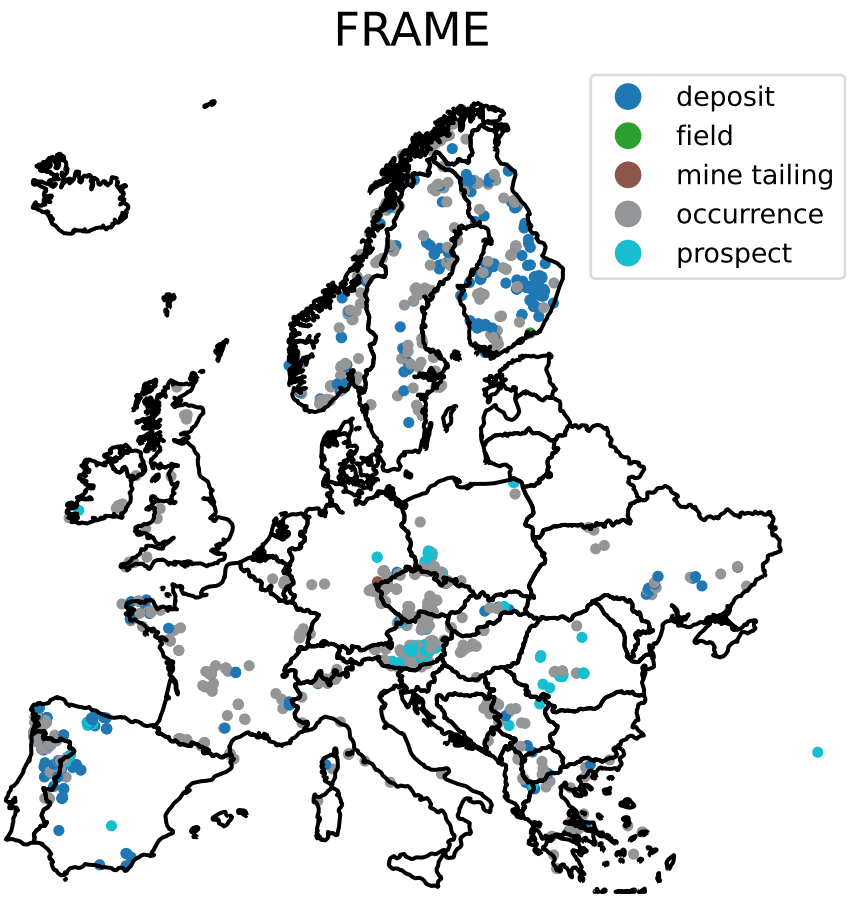

Fig. 1. Map of mainland Europe with FRAME project dataset of raw material occurrence points. The colour is determined by the "significant_importance" attribute of the points.

We also gather datasets of protected areas from multinational entities including Nature 2000, Emerald Network, Nationally designated areas (CDDA) and Unesco World Heritage Sites (Fig. 2). These areas can overlap with each other and have differing significance in terms of conservation criteria. However, all of them with or without overlaps with each other have the potential for land use conflicts as the criteria for conservation is probably less significant of a factor in determining conflicts in comparison to social aspects related to the areas (e.g. density of people nearby or using the PAs; Lèbre et al. 2020). Consequently, in our analyses the significance of the PAs is not attempted to be weighted and rather all are considered equally.

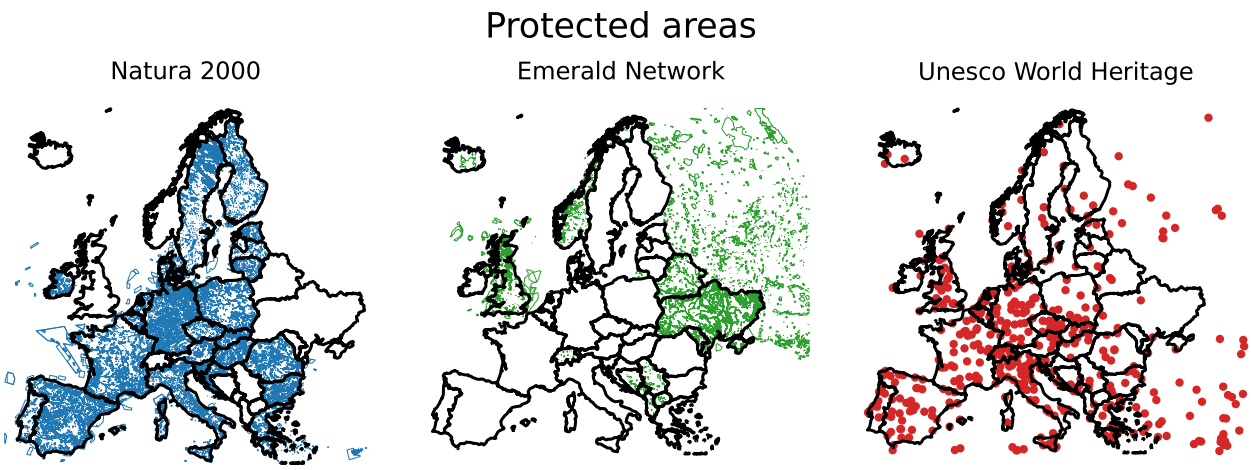

Fig. 2. Three datasets of protected areas in mainland Europe. Nature 2000 and Emerald Network are polygon layers while the Unesco World Heritage dataset consists of points.

The spatial analysis conducted on the dataset can be plainly described as an overlap analysis where it is determined where and how much the mineralisation overlaps with the PAs. However, the overlap analysis is expanded with geostatistical methods including e.g. using buffers around the mineralisation and/or the PAs, comparing different countries in terms of overlaps and comparing different mineralisation types. The scope of the analysis is still open and depends highly on the validity of the available mineralisation data. The assessment is being done as part of the Horizon Europe project CIRAN (Grant Agreement no. 101091483).

REFERENCES

European Commission 2020. Critical Raw Materials Resilience: Charting a Path towards greater Security and. Brussels. Available at: https://ec.europa.eu/docsroom/documents/42849

Lèbre, É., Stringer, M., Svobodova, K., Owen, J. R., Kemp, D., Côte, C., Arratia-Solar, A. & Valenta, R. K. 2020. The social and environmental complexities of extracting energy transition metals. Nature Communications 11, 4823. Available at: https://doi.org/10.1038/s41467-020-18661-9

Owen, J. R., Kemp, D., Harris, J., Lechner, A. M. & Lèbre, É. 2022. Fast track to failure? Energy transition minerals and the future of consultation and consent. Energy Research & Social Science 89, 102665. Available at: https://doi.org/10.1016/j.erss.2022.102665

Valenta, R. K., Kemp, D., Owen, J. R., Corder, G. D. & Lèbre, É. 2019. Re-thinking complex orebodies: Consequences for the future world supply of copper. Journal of Cleaner Production 220, 816–826. Available at: https://doi.org/10.1016/j.jclepro.2019.02.146

CIRCULAR BIOECONOMY SOLUTIONS AS A PART OF MINE CLOSURE

by

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BACKGROUND

Covering and landscaping of the mining waste areas is an essential part of mine closure. The characteristics of mine waste and mine waste facility along with the local climatic conditions define the requirements and guidelines for selecting the best available techniques and methods. Nowadays, in reclamation and closure plans the design of cover structure also determines the topsoil layer and greening. Selected and desired vegetation depends on the climatic conditions at the mine site, after-use plans, the cover structure, as well as the scale and shape of the waste facility. Vegetation establishment is challenging in northern conditions, where winters are long and temperatures low.

Sulphide-rich mining waste may produce harmful leachates when in contact or due to bacterial activity. This can lead to an undesirable environmental impact such as acid mine drainage (AMD) or changes in the water chemistry of catchment area. The primary objective of the cover structure is usually to minimise the amount of water and oxygen passing through the cover into the extractive waste (tailings or waste rock pile), to increase the alkalinity of infiltration water and to retain water for plants. In Finland, the covering has mostly based on till that meets these criteria. However, in future, suitable till may not be found in the vicinity of the mine site, which increase the transport costs and further on the closure costs. Optimising the cover structure and application of other materials may reduce the need of till, restrain the closure costs, promotes plant growth and further on prevent weathering.

Recently, the goals of circular bioeconomy and carbon neutrality have promoted new opportunities and solutions for covering structures. The addition of biochar to soil has shown promising results globally in the remediation of contaminated lands (Bolan et al. 2022, Penido et al. 2019). Moreover, the impact of biochar on plant vitality and vegetation establishment have been widely studied and yielding good results.

MATERIALS AND METHODS

The first studies in Finland and Northern Europe on the utilisation of biochar in mining waste cover solutions were started in 2017 with the support of the EU funding. Biopeitto 1 ("Biocover 1") project (2017–2020) was conducted as a collaboration project of Geological Survey of Finland (GTK), Natural Resources Institute Finland (Luke) and University of Oulu (OY). A dry cover was prepared using till, composted sewage sludge and biochar made by slow pyrolyzing. This organic matter containing "biocover" was shown to improve plant growth, retain water and reduce the transport of metals to plants and leachate. However, the results are based only on the results of few growing seasons and plant species used were not local origin (growing naturally in Lapland) (Pietilä et al. 2020).

In Kierroksia biopeittoon ("Biocover 2") project (2020–2023), the monitoring and development of biocover continued in collaboration of Luke and GTK with the support of the European Regional Development Fund. The primary object was to develop a long-term cover solution that reduces the environmental impact of mining waste areas. New organic waste and by-product materials generated in the Lapland region were used in the studies. In addition, mining companies and SMEs of the bio- and circular economy sector were networked to conduct a case study starting from wood waste and ending to the covering structures of mine rock site. Also, carbon footprint and costs of biocover were calculated (Hagner et al. 2023).

Initially, the project identified potential raw materials for bio-cover production in the Lapland region. Selected organic waste and by-product materials for further studies were composted sewage sludge (SS), biochar and ash produced from SS, biochar made from waste wood and forest harvest trees (spruce) and fly ash from energy production. Through laboratory, greenhouse and field experiment we investigated the impact of applying these materials on functioning of the cover's (leachate water quality and quantity), erosion and plant growth under challenging conditions. Additionally, the weathering and metal adsorption of the various biochar types was investigated (Fig. 1).

During the project, the underground lysimeter studies which started already in the previous Biopeitto 1 project, were continued. In addition, two laboratory experiments, new above-ground lysimeter study, two greenhouse experiments and field experiments in the old tailings area (square tests) were established. Experiments included water sampling, geochemical, physical and biological analyses, material characterisation, monitoring of the plant growth, sensor data measurements etc. In addition, tomography and LV-SEM were used in investigate the metal adsorption, weathering and wetting of biochar.

PRELIMINARY RESULTS

The performance of widely used till-based cover as a growing media for plants can be enhanced with new circular economy-based growth media components. Application of sewage sludge is a good way to increase plant growth. Biochar further increases plant growth and good vegetation cover has a beneficial effect on the performance of the cover solution (Fig. 2) (Hagner et al. 2021). Also, sewage sludge and fly ashes increased plant growth in greenhouse experiments (Heiskanen et al. 2022).

The water retention capacity of various biochar varied widely, affecting the water retention properties of the growing media and cover solution. Different biochar types have also other differences and for instance, it is necessary to ensure that polyaromatic hydrocarbons (PAH) concentrations are not too high.

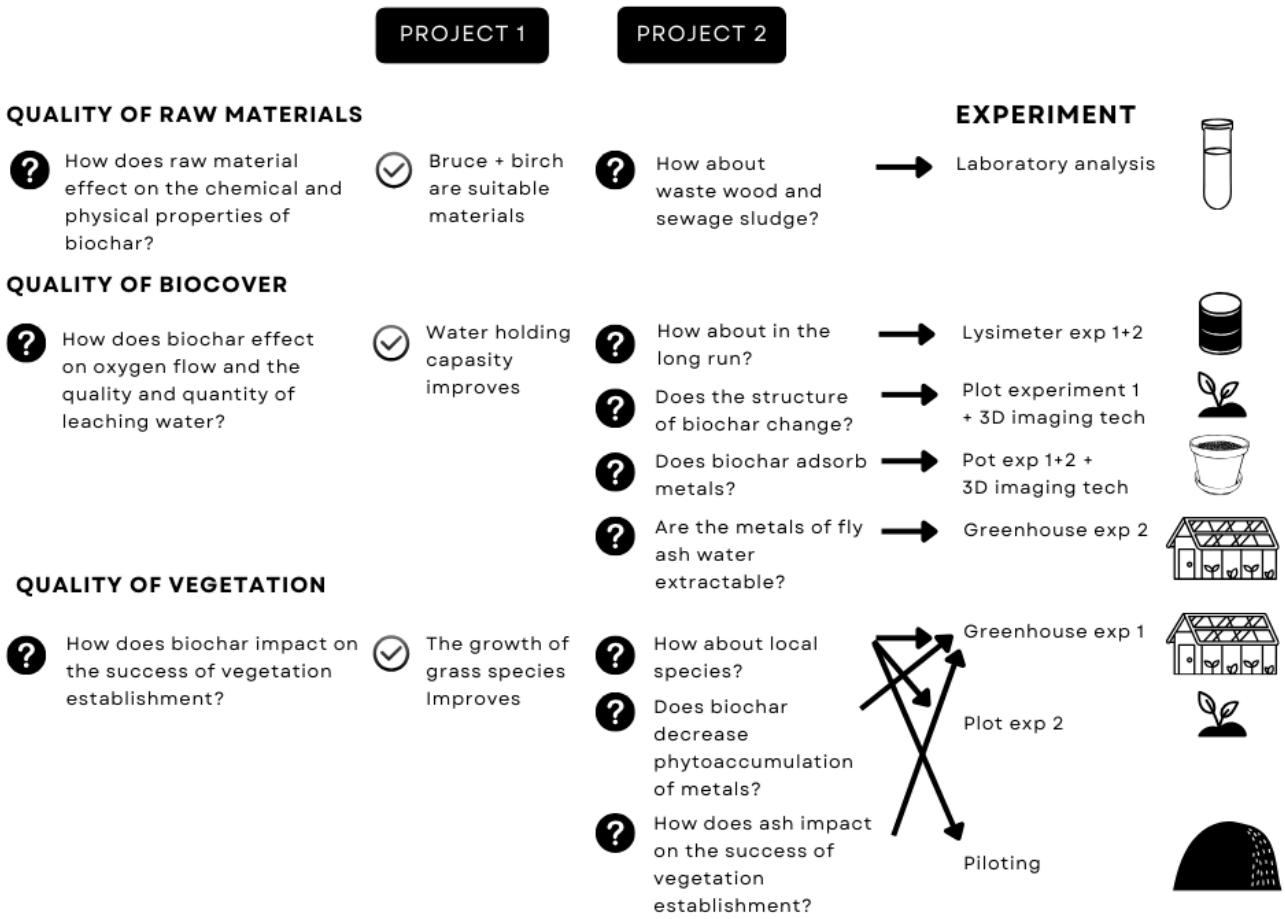

Fig. 1. Research questions and methods in Kierroksia biopeittoon project (project also includes the main results of previous Biopeitto 1 project). Image: Marja Uusitalo, Luke.

Studied biochars had no or minor effects to the leachate water quality after infiltration through the till cover. Instead, biochar and plants together reduced the quality of leachate water remarkably (ca. 30%). Based on studies at research laboratory the pore structure of biochar fills with water very slowly and weathering of biochar is slow. Just slight cracking was found after 50 freezing-melting cycles.

There was not clear evidence from the interaction between the mine water and the biochar types. However, the element contents of As, Ni, S, and U were slightly higher in wood-based biochar after the one and half years contact with mine water. Also, secondary mineral precipitation like gypsum roses was seen in biochar surfaces (LV-SEM).

In conclusion, bio-circular economy can serve the mining sector and provide additional options for establishing dry covers to the extractive waste facilities (Hagner et al. 2023). The development and expanding of the results will hopefully continue in Biopeitto 3 project in the near future.

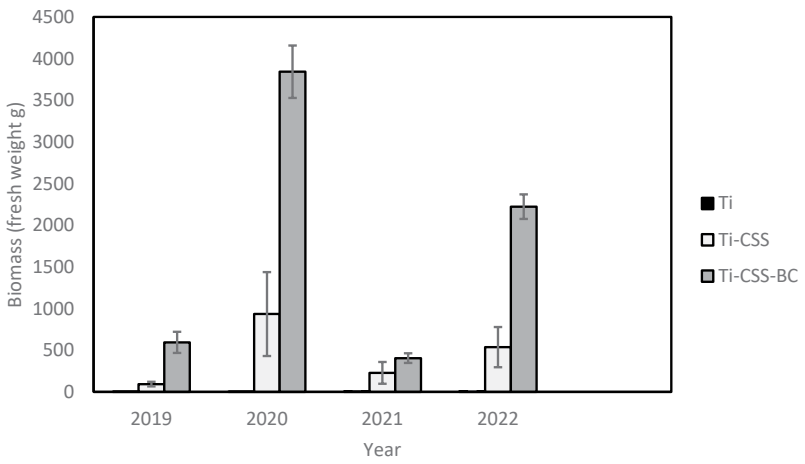

Fig. 2. Plant biomass in lysimeters with various growth medias containing Ti = till, Ti-CSS = till and sewage sludge compost, Ti-CSS-BC = till, sewage sludge compost and spruce biochar.

REFERENCES

Bolan, N., Hoang, S. A., Beiyuan, J., Gupta, S., Hou, D., Karakoti, A., Joseph, S. Jung, S., Kim, K.-H. & Kirkham, M. 2022. Multifunctional applications of biochar beyond carbon storage. International Material Reviews 67, 150-200.

Hagner, M., Uusitalo, M., Peltola, R., Rasa, K., Heiskanen, J., Ruhanen, H., Uotila, K., Vikki, K., Leinonen, I., Ranta, K., Hietanen, J., Tornivaara, A., Pietilä, R., Lahtinen, T., Kuva, J., Heikkilä, P. & Liwata-Kenttälä, P. 2023. Biokiertotaloudesta uusia ratkaisuja kaivosten jälkihoitoon: Kierroksia biopeittoon -hankkeen loppuraportti (Biopeitto 2). Luonnonvara- ja biotalouden tutkimus 86/2023. Helsinki: Natural Resources Institute Finland. 73 p. (in Finnish). Available at: http://urn.fi/URN:ISBN:978-952-380-780-8

Hagner, M., Uusitalo, M., Ruhanen, H., Heiskanen, J., Peltola, R., Tiilikkala, K. & Mäkitalo, K. 2021. Amending mine tailings cover with compost and biochar: effects on vegetation establishment and metal bioaccumulation in the Finnish subarctic. Environmental Science and Pollution Research. Available at: https://doi.org/10.1007/s11356-021-14865-8

Heiskanen, J., Ruhanen, H. & Hagner, M. 2022. Effects of compost, biochar and ash mixed in till soil cover of mine tailings on plant growth and bioaccumulation of elements: A growing test in a greenhouse. Heliyon e08838. Available at: https://doi.org/10.1016/j.heliyon.2022.e08838

Penido, E. S., Martins, G. C., Mendes, T. B. M., Melo, L. C. A., de Rosário Guimarães, I. & Guilherme, L. R. G. 2019. Combining biochar and sewage sludge for immobilization of heavy metals in mining soils. Ecotoxicology and Environmental Safety 172, 326–333.

Pietilä, R., Hagner, M., Heiskanen, J., Juutinen, M., Lahtinen, T., Liwata-Kenttälä, P., Mäkitalo, K., Nuottimäki, K., Peltola, R., Ruhanen, H., Sarala, P., Seitsaari, M., Tornivaara, A. & Uusitalo, M. 2020. Biopeitto-projekti. Biohiilen hyödyntäminen kaivannaisjätteiden peittomateriaaleissa ja viherrakentamisessa. Geological Survey of Finland, Open File Research Report 51/2020. 81 p. (in Finnish). Available at: https://tupa.gtk.fi/raportti/arkisto/51_2020.pdf

ROBOMINERS: A PROJECT WITH DISRUPTIVE INNOVATION POTENTIAL

by

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INTRODUCTION

The H2020 Resilient Bio-inspired Modular Robotic Miners (ROBOMINERS) project, which started in June 2019 and is set to conclude in November 2023, is creating a prototype of a bio-inspired, modular, and reconfigurable robot-miner. This robotic miner was designed to exploit small and hard-to-reach mineral deposits that are not economically feasible to extract using conventional mining methods.

The ROBOMINERS prototype will operate, navigate, and selectively mine in underground environments. To complement the development of the physical prototype, the ROBOMINERS project is also establishing a mining ecosystem through simulations, modelling, and virtual prototyping. The prototype is being subjected to rigorous testing under various scenarios to evaluate its mining capabilities and resilience, and to demonstrate the potential of this new technology to exploit mineral resources effectively. Most of the key functions of the robot-miner are being validated to a Technology Readiness Level (TRL) of 5, during intensive field trials in controlled environments. Development of the prototype is planned to continue in the upcoming years to bring this unique technology line closer to the market.

WHY ROBOMINERS IS RELEVANT

The mining industry, known for its high number of fatalities and injuries, poses significant dangers to human workers. In addition, the industry often involves heavy equipment used in confined spaces with poor ventilation, high temperatures, water inrushes, and even explosive atmospheres. Due to these inherent risks, the mining industry holds tremendous potential for the adoption of robots. Today, driverless haul trucks and automated drill rigs are already in use in open-

cast mines, and the development of robots capable of operating underground and underwater is underway for inspection and testing purposes.

As technology continues to advance, mining robots have the potential to extract minerals from greater depths in the Earth's crust, particularly in environments that are harmful to human workers due to high temperatures and rock stress. These conditions often lead to increased mining costs due to safety and engineering requirements.

ROBOMINERS was conceived to facilitate access to mineral deposits that were previously too expensive, dangerous or difficult to extract in an economically and environmentally sustainable manner.

Specifically, the ROBOMINERS prototype, powered by artificial intelligence, can optimise navigation and mineral extraction in challenging subterranean environments. This supports faster, lower impact, underground extraction of critical mineral deposits within Europe. The selective excavation techniques also allow focusing extraction on the richest grades, avoiding rock waste and fostering process efficiency. By enabling efficient, targeted extraction of raw materials, ROBOMINERS can directly help fulfil the ambition of the proposed EU Critical Raw Materials Act to boost domestic production of critical metals and minerals to 10% of EU demand while upholding social and environmental standards in line with the European Green Deal.

The development of the ROBOMINERS prototype also serves as a foundation for further exploration in robotics, focusing on scalability, resilience, reconfigurability, self-repair, and operation in harsh environments (Fig. 1). Additionally, advancements in sensors and artificial intelligence are pursued to address collective behaviour and selective mining processes. The project emphasises the convergence of technologies necessary to establish a comprehensive mining ecosystem, including mine design, ore processing, and mill pumping.

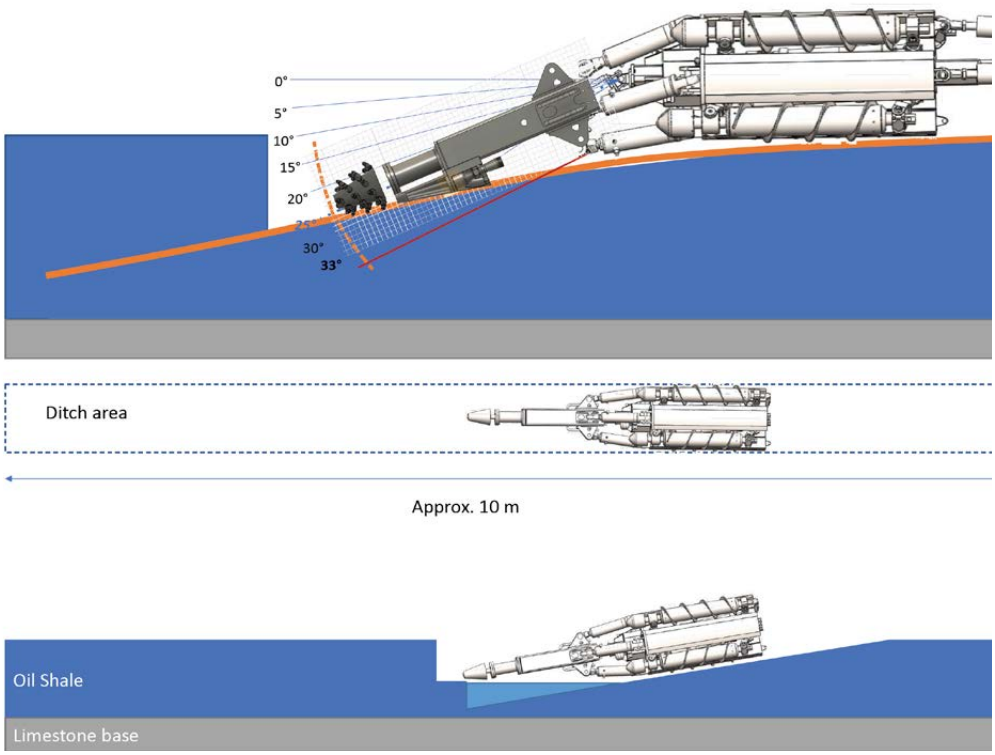

Fig. 1. Sketch of the RM1 production tests.

WHY ROBOMINERS BRINGS A PARADIGM SHIFT

In pre-20th century mines, extraction primarily relied on manual methods, leading to limited underground mine excavations that focused on mineralised areas. This historical context explains why mine tunnels during the Roman era up until the pre-industrial revolution were notably narrow. Moreover, the use of child labour was prevalent in mining operations during this period. The small size and agility of children made them suitable for tasks requiring manoeuvring in tight spaces or operating tools in cramped conditions. Until the end of the 19th century, children as young as five years old were commonly employed in underground mines, enduring gruelling working hours of up to 12-16 hours a day, six days a week. They faced brutal treatment from mine owners and overseers, who enforced strict discipline through physical punishments and verbal abuse. In the late 19th and early 20th centuries, awareness of the dire conditions faced by child miners began to grow. Efforts were made to improve legislation and labour standards to protect children from exploitation, and the emergence of labour unions and advocacy groups played a significant role in raising awareness about child labour abuses and pushing for reforms.

With the advent of new technologies and the Industrial Revolution's transformative impact on various industries, mining also experienced significant changes. Steam-powered drills replaced hand tools, revolutionising the speed and efficiency of drilling and extraction operations. Additionally, pneumatic drills powered by compressed air emerged as a game-changing technology, further enhancing excavation capacity and productivity. Alongside these advancements, the introduction of dynamite as a safer and more powerful explosive replaced black powder. Dynamite proved to be more stable, easier to handle and detonated using a blasting cap or fuse. These technological breakthroughs allowed for the creation of larger tunnels and led to overall improvements in working conditions for miners.

While the creation of larger tunnels improved working conditions, it also resulted in an increase in waste rock production. Waste rock, typically devoid of valuable minerals, accumulated during the access to mineralised zones and within those zones where it mixed with ores, causing dilution that required further processing and resulting in larger volumes of tailings.

In modern times, mines have transitioned to full mechanisation, with tunnels designed to accommodate heavy equipment such as dumpers and excavators. However, this shift has led to increased amounts of waste rock generation. Additionally, smaller mineralised areas within a deposit are often left behind due to economic considerations, as it may not be viable to extract them. Compounding this challenge, ore grades have been decreasing in many mining operations globally, necessitating the extraction of larger volumes to maintain economic viability. The extraction of such large volumes is only feasible with the use of large machinery, resulting in the production of significant amounts of waste rock and tailings.

ROBOMINERS has the potential to transform this paradigm owing to its size.

The ROBOMINERS prototype is composed of two modules plus a boom. It measures 5 metres in length and boasts a diameter of nearly 1 metre. Currently it is tele-operated, but its digital twin possesses the capability to autonomously open tunnels and operate underground without human intervention. This groundbreaking advancement unlocks unprecedented possibilities for the future of mining operations.

One of the key advantages of the ROBOMINERS prototype is its ability to minimise waste rock and tailings generation. With precise excavation techniques, it can extract minerals from small deposits and recover all existing ores, significantly reducing the environmental impact of mining operations. Additionally, ROBOMINERS operates without the requirement for ventilation shafts or the pumping of underground water, streamlining the mining process and minimising operational costs and resource consumption.

ROBOMINERS' capacity to operate at great depths, which are inaccessible to humans due to the Earth's geothermal gradient, unveils a vast potential for mineral extraction. While surface mineral deposits have been extensively exploited, there remains untapped mineral wealth at deeper levels within the Earth's crust. This presents a solution to the increasing demand for raw materials, ensuring a sustainable supply for various industries.

DEEP MINING

The main obstacles to the construction of deep mines, i.e. mines capable of reaching mineral deposits located at depths below 1,000 m, are of three kinds (Correia et al. 2023): physical, geotechnical and economical.

The Earth's geothermal gradient causes the physical constraints. For example, in standard continental crust, a typical geothermal gradient within the first 3 to 5 Km of Earth's surface is about 25°C/km (DiPietro 2013). This means that the temperature of a drift wall at approximately 2 km depth would reach 50 °C, which poses risks to workers, such as exhaustion or heatstroke. Such challenges are exemplified in the Mponeng mine in South Africa that operates at depths ranging between 3,160 m and 3,740 m, being the deepest mine in the world, where rock wall temperatures can reach 66 °C (Wadhams 2011).

Geomechanical problems are caused by increased stresses in the *in situ* rock at greater depths, making strain control more difficult. Deep-mine designs also require an understanding of rock fracture processes and the development of numerical methods for structural analysis, monitoring of seismic activity, and development of semi-empirical design concepts.

Economic difficulties are mainly related to the amount of rock that must be excavated to reach deposits over 1,000 metres deep. Unless the deposit is large and the ore deposit rich, the economic feasibility of the project depends not only on the cost of excavation but also on the costs of more advanced infrastructure (ventilation, safety, pumping, etc.), operation and maintenance.

Besides, the deployment of ROBOMINERS brings the possibility of making mines "invisible." By excavating small tunnels and conducting pre-processing underground, the impact on the surface is greatly reduced. This addresses one of the primary concerns of the public regarding mining, including landscape destruction and environmental consequences. The adoption of ROBOMINERS can help alleviate opposition to mining by mitigating its visible effects.

Financially, the implementation of ROBOMINERS offers a more cost-effective approach compared to conventional mining. While operational costs will be constrained by productivity parameters, the initial investment and setup costs are significantly lower than the infrastructure and capital expenses of traditional mines.

VALIDATING TECHNOLOGY DEVELOPMENT THROUGH FIELD TRIALS

In July and August 2023, the ROBOMINERS project tested its full-scale prototype, RM1, during field trials in Estonia. The demonstration aimed to showcase the prototype's selective mining capabilities under real-world conditions, particularly in following the oil-shale layer in between limestone layers.

This played a pivotal role in validating key functions of the RM1 prototype, ultimately advancing its Technology-Readiness-Level (TRL) to level 5.

Fig. 2. RM1 drilling at the test site in Kunda. Credit: Jussi Aaltonen, Tampere University.

CONCLUSIONS

Robotics can catalyse an underground mining transformation by enabling selective, minimised-diameter galleries suited only to ore extraction. Eliminating ventilation, drainage, and access requirements of human miners shrinks infrastructure needs. Following ROBOMINERS' vision, remote robotic excavation can radically improve worker safety, efficiency, and resource access. Mines become invisible as robots operate deep underground, navigating precisely to high-grade ore. By extracting only valuable material, robotic mining dramatically lowers costs and environmental impacts.

Moreover, embracing this innovation positions the EU for technological leadership in sustainable mining. ROBOMINERS' selective techniques exemplify how strategic adoption of robotics can balance resource extraction with ecological stewardship for a circular economy. Propelling such advancement will be pivotal for the EU to achieve its vision of environmental responsibility and socio-economic prosperity. The continent can lead a new paradigm where automated mines provide raw materials for a thriving society without sacrificing the natural world.

ACKNOWLEDGEMENTS

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REFERENCES

Correia, V., Hartlieb, P. & Falck, W. E. 2023. The Future of Mining: technical progress and its implications. In: Peppoloni, S. & Di Capua, G. (eds) Geoethics for Future: Facing Global Challenges. Elsevier. (forthcoming)

DiPietro, J. A., 2013. Landscape Evolution in the United States // Landscape evolution in the United States. An introduction to the geography, geology, and natural history. (1. ed.). Amsterdam: Elsevier.

Wadhams, N. 2011. Gold Standards: How miners dig for riches in a 2-mile-deep furnace. Wired 19(3), p. 42.

APPLICATION OF THE PROSPECT SCALE GREENPEG EXPLORATION TOOLSET FOR PEGMATITE: THE WOLFSBERG LI PEGMATITE FIELD, EASTERN ALPS

by

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The European innovation project GREENPEG, financed by the EU HORIZON 2020 programme, develops an integrated, multi-method toolset for exploring niobium-yttrium-fluorine (NYF) and lithium-caesium-tantalum (LCT) pegmatites in different European settings. Methodology testing is performed on three scales (province, district, prospect) and at three representative European demonstration sites.

Wolfsberg, located in Carinthia, Austria, is one of the brown field demonstration sites chosen to test the best combination of exploration methods suitable for the local geological, geographical and topographical conditions of the pegmatite field. Exploration methods range from province to prospect scale. While various geochemical, geophysical, and geological surveys have been completed at the Wolfsberg site, some surveys are pending so that work is still in progress; but available data allow a preliminary appraisal of already applied methods on prospect scale.

The spodumene-bearing Li pegmatites at the Wolfsberg site are part of the Austroalpine Unit Pegmatite Province that extends roughly E-W across the eastern Alps. They were emplaced into Palaeozoic sedimentary rocks during Permo-Triassic lithospheric extension (Schuster & Stüwe 2008, Thöni et al. 2008). After emplacement, the dykes underwent a complex tectono-thermal evolution with intense deformation and upper amphibolite to eclogite facies high-pressure

metamorphism related to the Cretaceous Eo-alpine event (Janák et al. 2004, Stüwe & Schuster 2010) followed by Cenozoic alpine folding (Putz et al. 2006).

The pegmatites are poorly exposed at the surface and their presence is mainly indicated by boulders, but they have been drilled and are accessible in several linked underground adits. Paragneiss and mica schist intercalated with eclogitic amphibolite and minor marble form the host rocks. The dyke-shaped pegmatites have an average thickness of around 2 m (max. thickness 5.5 m) and can be traced over a length of 1.5 km and to 450 m depth.

Geological maps (scale 1:50.000, Geologische Bundesanstalt 1980) and a detailed prospect scale map by Göd (1989) serve as the basis for structural mapping and analysis in the field both on surface and underground. The pegmatites run subparallel to the lithological layering on the limbs of a regional-scale, gently ESE-plunging antiform structure. Most of the dykes are located on the northern limb, notably at the contact zone between amphibolite and mica schist. Mapping also revealed a spatial association of the inferred outcropping area of the spodumene pegmatites with (i) strongly foliated mica gneisses that contain ample foliation-parallel quartz veins and barren pegmatites and, (ii) conspicuous so-called "paramorphose schists" containing large kyanite after andalusite pseudomorphs, that together may serve as a marker horizon.

Ground sampling and ground geophysics measurement campaigns used the same profile lines oriented perpendicular to the strike of the pegmatites and host rock foliation. Data of different types can therfore be integrated and evaluated. Steep terrain and dense coverage of high trees unfortunately inhibited the usage of drone-borne measurements, like radiometry and hyperspectral imaging.

Prospect scale soil Ah- and C-horizon mapping and stream sediment sampling proved to be successful exploration methods at the Wolfsberg site. Strong anomalies for Li in C-horizon samples, and less defined also in Ah-horizon samples, are spatially coincident with the zone of subcropping spodumene pegmatites in the amphibolite-mica schist contact zone. Elevated Li concentration in stream sediment samples likewise is a strong indicator for subcropping Li pegmatites. Hence, both C and Ah soil samples as well as stream sediment samples could be used as pathfinders to spodumene pegmatites.

Geochemical wall-rock halo mapping using bulk rock geochemistry and *in situ* portable XRF measurements performed along selected drill cores intersecting >2 m thick pegmatites reveal an enrichment of pegmatite-related elements, most significantly Li, Cs, Sn and Rb at the pegmatite-wall rock contact. Halos reach a width of ca. 1m (pXRF, Rb, Sn) to up to ca. 4 m (bulk rock, Li, Cs, Sn, Rb). They may enhance element anomalies in soil above subcropping pegmatites.

Borehole logging (wireline logging) was performed at nine boreholes (four situated in the underground mine, five surface boreholes) transecting the pegmatite bodies. In addition, 30 core samples were analysed for their petrophysical properties. The obtained physical and chemical properties of the intersected lithologies (like electrical resistivity, chargebility, magnetic susceptibility, density (lab data), P- and S-wave velocities,natural/spectral gamma ray counts) provide key parameters for choosing and adjusting geophysical survey methods and for the interpretation of the results. Thicker pegmatite dykes show lower ThO_2 values than the surrounding mica schist and higher values in the amphibolite. However, halos of pegmatites showing either enriched or depleted uranium, thorium or potassium could not be detected and are likely absent or of very low amplitude. The borehole logs reveal a contrast in magnetic susceptibilities between pegmatite (very low) and host rocks even though the magnetic susceptibilities of the latter are low as well. Of significant importance are resistivity and chargeability contrasts between pegmatites bodies and both amphibolite and mica schist.

Results of ERT surveys along three long profiles (length: 950 m, electrode spacing: 10 m) and two short profiles (length: 216 m, electrode spacing: 3 m) enable the distinction between high resistivity amphibolite and lower resistivity mica schist. The latter can be even further subdivided into a lower resistivity mica schist (MS1) and a higher resistivity schist MS2. A major, roughly N-dipping fault zone is inferred from a narrow low-resistivity zone reaching towards the surface. It marks the border between the high resistivity amphibolite at depth in the north and an anomalously low resistive zone (<50 Ohm*m) in the center of the profile that is interpreted to representing the amphibolite-mica schist contact zone where the two lithologies are interlayered. Although individual pegmatite veins could not be detected by this method and setup the knowledge that spodumene pegmatites are concentrated in the contact zone defines the low-resistivity zone as a marker that could be used to identify potential drilling target zones with the help of ERT profiles outside the mine area.

Amphibolite and mica schist may also be distinguished in Ground Radiometry surveys along the profile lines showing the strongest gradients of low/high radioactivity between amphibolite (low radiation) and mica schists (high radiation) in the contact zone. Pegmatite dykes, however, could not directly be detected by this method.

This also applies to ground magnetic measurements that furthermore can distinguish the two main host rock lithologies only in areas where the soil cover is thin. Hence, using the magnetic and radiometric contrasts these two methods provide additional tools for tracing of the amphibolite-mica schist contact zone and as such the potential pegmatite-bearing corridor.

In summary, no method alone is not able to provide sufficient data for identifying pegmatite bodies or fertile corridors. A bundle of methods complementing each other is required to identify pegmatite bodies. For choosing the right tools, a comprehensive knowledge of the local geology and detailed mapping is fundamental. This is particularly important in conditions like Wolfsberg where pegmatite bodies cannot be detected directly but where potential zones for pegmatite emplacement can only be found indirectly using geological background knowledge. A sound understanding of the 3D structure is essential to define the location and orientation of survey lines and to delineate and follow potentially fertile corridors. In the case of Wolfsberg, the amphibolite and thus, the amphibolite-mica schist contact zone cannot be followed farther to the east at the surface, in contrast to the spatially associated quartz vein-rich gneisses and the paramorphose schists. Stream sediment samples taken a few kilometres east of the mine do not show significant Li concentrations. Due to the ESE-plunge of the antiform, however, the contact zone, and potentially associated spodumene pegmatite dykes, would be located at increasingly deeper levels towards the east, provided the amphibolite lens does not thin out before. This could be tested with an ERT survey checking whether a low resistivity anomaly occurs at depth. Likewise, the surveys could be extended to the southern limb of the antiform for more detailed exploration of this area and to check whether and where more drilling may be feasible and worthwhile.

REFERENCES

Geologische Bundesanstalt 1980. Geologische Kart der Republik Österreich, 1:50.000, Blatt 188, Wolfsberg. Wien: Geologische Bundesanstalt.

Göd, R. 1989. The Spodumene deposit at "Weinebene", Koralpe, Austria. Mineralium Deposita 24, 270–278.

Janàk, M., Froitzheim, N., Luptàk, B., Vrabec, M. & Krogh Ravna, E. J. 2004. First evidence for ultrahigh-pressure metamorphism in Pohorje, Slovenia: Tracing deep continental subduction in the Eastern Alps. Tectonics 23, TC5014. Available at: http://dx.doi.org/10.1029/2004TC001641

Putz, M., Stüwe, K., Jessell, M. & Calcagno, P. 2006. Three-dimensional model and late stage warping of the Plattengneiss Shear Zone in the Eastern Alps. Tectonophysics 412, 87–103. Available at: https://dx.doi:10.1016/j.tecto.2005.10.003

Schuster, R. & Stüwe, K. 2008. The Permian Metamorphic Event in the Alps. Geology 36/8, 303–306. Available at: http://dx.doi.org/10.1130/G24703A.1

Stüwe, K. & Schuster, R. 2010 Initiation of Subduction in the Alps: Continent or Ocean? Geology 38(2), 175–178. Available at: http://dx.doi.org/10.1130/G30528.1

Thöni, M., Miller, Ch., Zanetti, A., Habler, G. & Goessler, W. 2008. Sm-Nd isotope systematics of high-REE accessory minerals and major phases: ID-TIMS, LA-ICP-MS and EPMA data constrain multiple Permian-Triassic pegmatite emplacement in the Koralpe, Eastern Alps. Chemical Geology 254, 216–237. Available at: https://doi.org/10.1016/j.chemgeo.2008.03.008

INNOVATIVE DEEP-SEA IMPACT ASSESSMENT. TRIDENT: NEW IMPACT ASSESSMENT TECHNOLOGIES FOR SUSTAINABLE DEEP-SEA EXPLORATION

by

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Critical raw materials such as lithium, cobalt and graphite are key for ensuring the strategic value chain in Europe. Most of these materials are mined on land with significant environmental and societal impacts. In the present increasingly high-demand scenario, deep-sea mining seems to be unavoidable in the future, hence, the need for anticipating deep-sea activities and set in place strong monitoring and environmental impact assessment tools and procedures.

The project aims at developing new technological tools for deep-sea impact assessment. TRIDENT's system will use advanced technology and innovative solutions to operate autonomously in remote areas under extreme conditions. It will provide real-time data to permitting and supervising authorities to ensure compliance with international and national legal frameworks. The project will complement all relevant physical, chemical, geological, and biological parameters already known to be measured at the sea surface, midwater, and seabed. TRIDENT will also identify gaps in methods of real-time data gathering, build data sets and develop the technological solutions to address them.

Project objectives are to: 1) Develop an integral environmental impact assessment capability, 2) Advance the understanding of geological, biological and environmental processes, 3) Develop an innovative dynamic infrastructure for real-time positioning, navigation, communication and awareness of deep-sea activities and monitoring systems, 4) Develop an innovative mobile autonomous high-tech laboratory transferred into the field, 5) Develop a holistic governance framework for Europe's Ocean resources sustainable exploitation, 6) Perform preparatory campaigns and a final demonstration in a representative environment, and 7) Lead the creation of a new commercial ecosystem driven by a cluster of European service and technology providers, satisfying client requirements globally. The project will ultimately empower a shared responsibility to supervise and monitor deep-sea activities, and simultaneously preserve and enhance marine habitats, supporting environmentally sustainable blue economy.

By using interactive means, this poster aims to achieving three objectives. First, raising awareness of the goals and importance of the project. Second, scoping the interest of stakeholders about TRIDENT's objectives. And third, identifying relevant stakeholders to build synergies and collaborations.

GEOCHEMISTRY, PROVENANCE, AND TECTONIC SETTING OF PALEOPROTEROZOIC METAVOLCANIC AND METASEDIMENTARY UNITS OF THE ALUTAGUSE ZONE, NORTH ESTONIA – A COMPARATIVE STUDY WITH THE SOUTH SVECOFENNIAN ZONE

by

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The research delved into the geochemistry of Paleoproterozoic metasedimentary and metavolcanic units in the Estonian Alutaguse and South Svecofennian (SS) zones (i.e. Ladoga, Saimaa, Häme Belt, Uusimaa Belt zones), offering insights into the Svecofennian Orogeny's tectonic progression over Eastern Fennoscandia (Fig. 1) Metasedimentary units generally correspond to micaceous gneisses (± Grt ± Crd ± Sil), and the metavolcanic ones to ortho-amphibolites and pyroxenic gneisses (Bogdanova et al. 2015. Soesoo et al. 2020). By merging historical data with new samples, classifications emerged, with High-SiO_2 (> 63 wt%) metasediments aligning with litharenites and Low-SiO_2 (< 63 wt%) samples with graywackes and shales. TAS classifications placed metavolcanic units in the sub-alkaline series. Weathering indices, including CIA, PIA, CIW, and ICV, were applied to metasediments, while AI, CCPI, WIP, and SI were used for metavolcanic samples.

High-SiO_2 (>63 wt%) samples from both zones mirror UCC characteristics, while Low-SiO_2 (<63 wt%) align with PAAS, highlighting varied source materials and high weathering degrees. In metavolcanics, Alutaguse presents elevated weathering and alteration indices, enhanced Th/U ratios, and high SO_3 wt% values, indicating high weathering and possible hydrothermal processes. Conversely, SS metavolcanics indices suggest limited alteration. A summary of sample major element data concentrations is presented in Figure 2.

The High-SiO_2 metasediments, for both Alutaguse and SS, lean towards felsic origins. Alutaguse has a marginally higher Al_2O_3/TiO_2 ratio, indicating a more pronounced felsic source. A–CN–K triangular plots, discriminant plots, and K-Rb relationships all corroborate this intermediate to felsic magmatic origin. For Low-SiO_2 metasediments, Alutaguse samples primarily suggest mafic to intermediate origins, with notable graphite-bearing mica gneisses in the mafic zone. In contrast, SS gravitates towards intermediate sources. South Svecofennian Low-SiO_2 samples follow the magmatic trend towards mafic compositions. However, while most of these samples show signs of a magmatic origin, a subset from the Ladoga and Saimaa regions have characteristics more commonly associated with sedimentary addition. TiO_2–Ni plots and transition element concentrations further differentiate the two areas, with Alutaguse samples aligning more with sedimentary trends, while SS samples lean towards mafic magmatic compositions. Ratios such as La/Sc and La/Co underscore a similar intermediate-mafic trend for Low-SiO_2 samples.

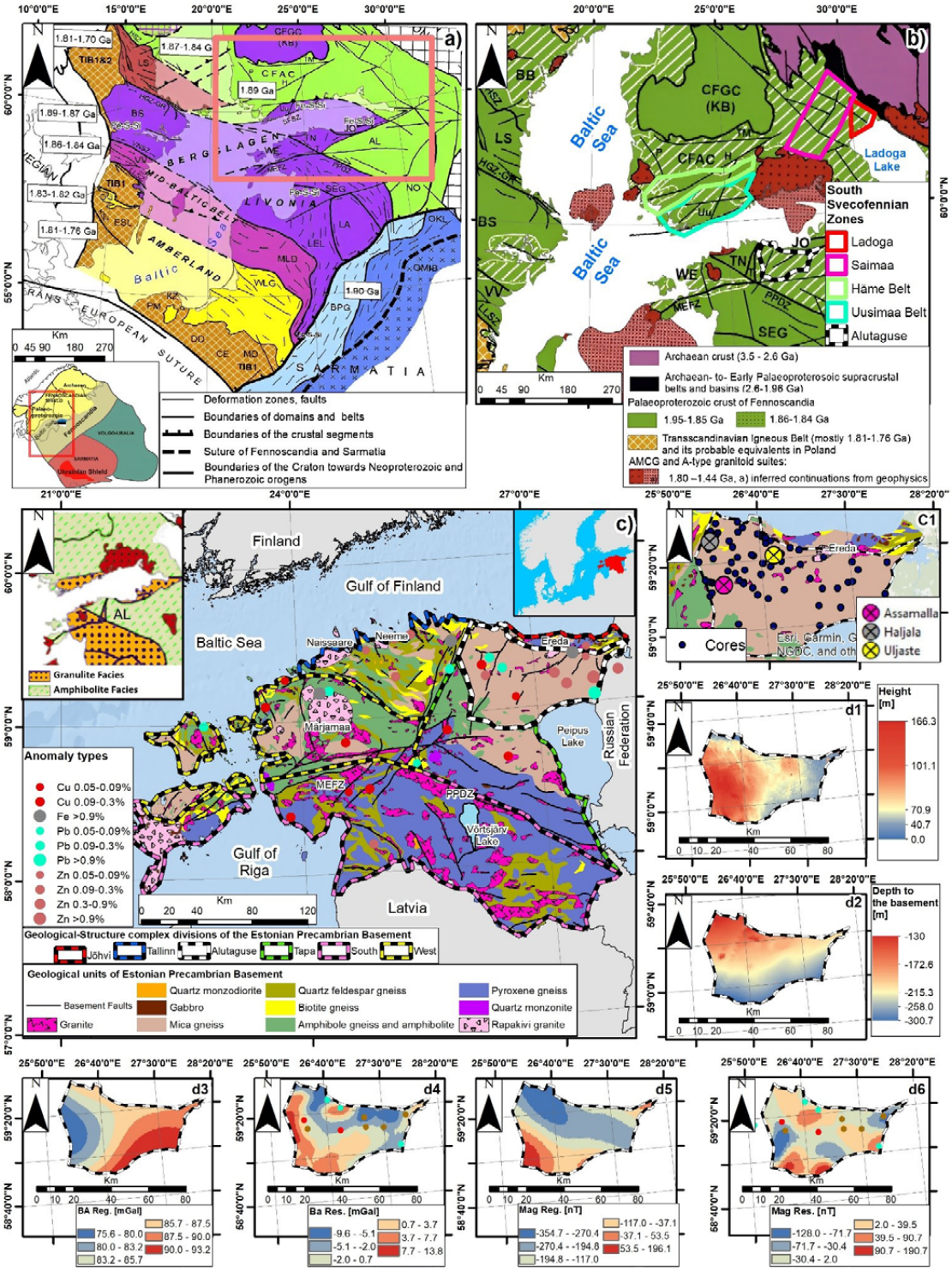

Fig. 1. Geological setting of the study zone, highlighting key features: a) Central and southern Svecofennian orogens (SO) crustal structure crosses the Baltic Sea. b) Major Palaeoproterozoic tectonic zones over the Fennoscandian area. c) Geological map scheme of the Precambrian basement of Estonia, showing geochemical anomalies according to Soesoo et al. (2020), and the upper right-corner inset showing the distribution of granulite- and amphibolite facies metamorphic rocks. Redish symbols correspond to Rapakivi lithologies. modified from Bogdanova et al. (2015). The anomaly symbols represent the most prominent metal of the mineralisation c1) Zoom of the geological basement map of the Alutaguse zone, depicting the location of the cores and the prominent metallogenic Alutaguse zones. d) Geophysical maps of the Alutaguse zone depicting the 1) 10 x 10 m topography, 2) Depth to basement, 3) Bouguer gravitational anomaly, 4) residual Bouguer anomaly, 5) Regional magnetic anomaly, 6) Residual magnetic anomaly. Please refer to Bogdanova et al. (2015), Soesoo et al. 2020, Solano-Acosta et al. 2023 for further information and a comprehensive understanding.

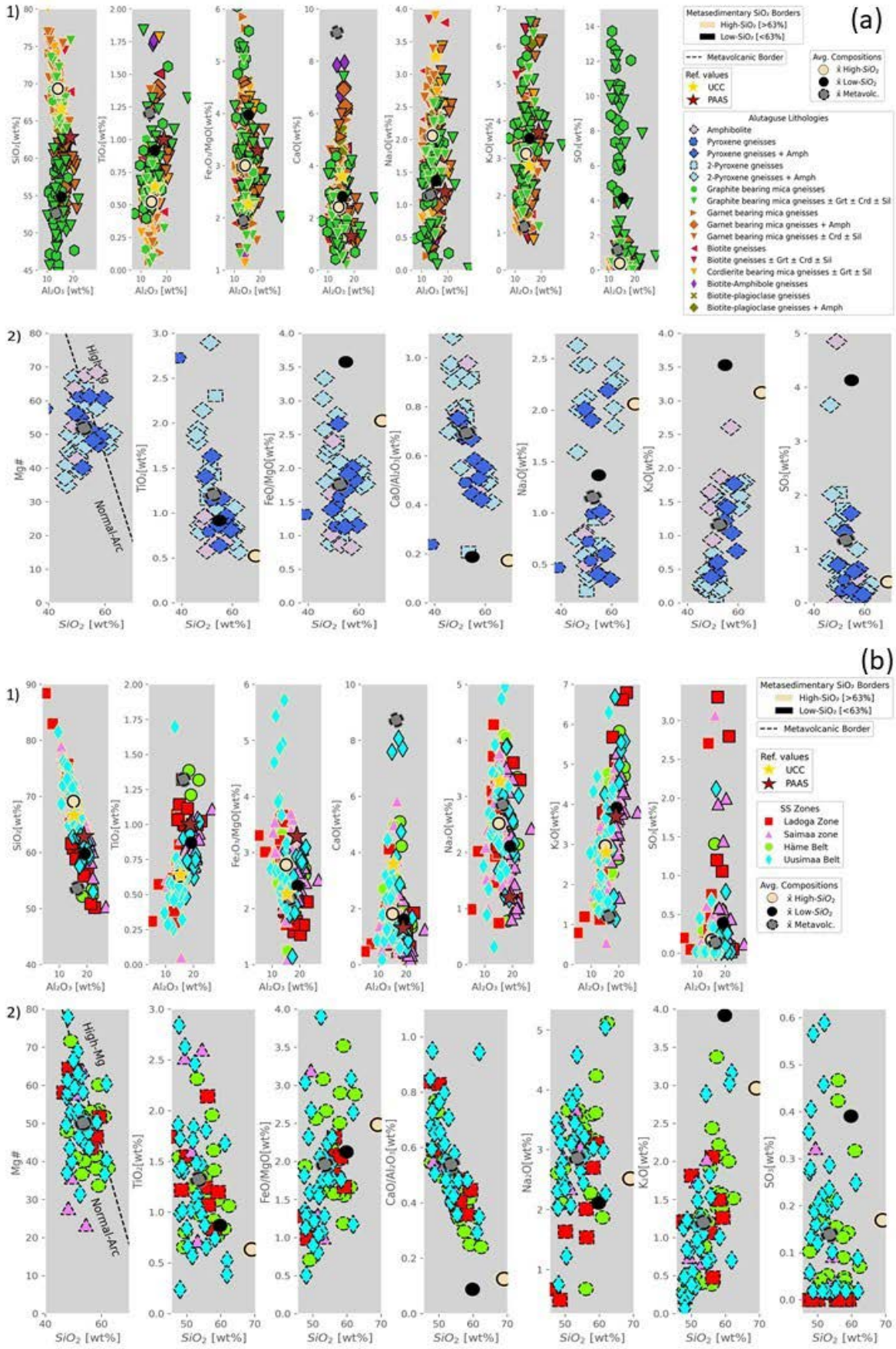

Fig. 2. a) Alutaguse and b) South Svecofennian (SS) samples bivariant Harker-plots. 1) Metasedimentary Major oxides vs. Al_2O_3. 2) Metavolcanic major oxides vs. SiO_2. Sample boundaries represent sample groups: High-SiO_2 in wheat, Low-SiO_2 in black, and metavolcanics in dashed-grey.

In assessing sedimentary sorting, recycling, and maturation, textural maturity emerges as a crucial marker, influenced by diverse grain, morphological, mineralogical, and geochemical profiles. For High-SiO_2 samples, both Alutaguse and SS present pronounced silica enrichment, indicated by elevated SiO_2/Al_2O_3 ratios, with Alutaguse highlighting significant sorting and maturation through its high chondrite-normalised Gd/Yb values. These High-SiO_2 samples also lean towards increased Zr/Sc ratios, suggesting notable sediment reworking, especially in the SS samples. When comparing Low-SiO_2 samples, both Alutaguse and SS demonstrate heightened geochemical immaturity, with narrower Al_2O_3/TiO_2 ranges and K_2O/Na_2O ratios above unity. However, SS Low-SiO_2 samples distinctly align with mature, recycled sediments in provenance discrimination plots, signifying contributions from older rocks. Across both categories, trace elements like Zr, Th, and Sc emphasise sedimentary origins and recycling, with SS High-SiO_2 samples showing particularly enhanced sedimentary reworking. Notably, negative Sr anomalies prevalent in both Alutaguse and SS metasediments typify Archean-Proterozoic aged recycled environments.

Derived sediments illuminate the nuanced relationship between geochemical attributes and tectonic environments. Through advanced discriminant-function-based multidimensional diagrams, this study identified that high-silica samples from both Alutaguse and SS metasediments predominantly align with continental rift zones, while select low-silica samples hint at collisional settings. Stable minor elements further supported the metasediment's affinity to the continental island arc (CIA) zone. Although specific geochemical markers suggest a continental arc origin, the inherent arc-like traits of the continental crust mandate interpretive caution.

Alutaguse metavolcanics exhibit tholeiitic tendencies and are metaluminous, with elevated Nb and diminished Zr levels, hinting at enriched and depleted mantle origins. Conversely, SS metavolcanics lean towards calc-alkaline orientations and present a mixed mantle source leaning slightly towards depletion, as their δNb values indicate. Both Alutaguse and SS samples predominantly align with garnet-lherzolite melting patterns in La/Yb vs. Zr/Nb and La/Sm vs. Sm/Yb plots, showcasing their intricate tectonic processes and highlighting the influence of both mantle depletion and enrichment events.

Alutaguse samples, with their distinct Th/Nb and Th/Zr elemental ratios, primarily point towards an asthenospheric mantle origin, emphasising a deeper connection with mantle processes. Conversely, SS samples, marked by elevated Nb/Zr, Ba/Th, and U/Th ratios, hint at a significant influence from the subducted oceanic crust. This delineation between the two sets not only showcases the profound role of elemental ratios like Nb/Zr, Th/Zr, Ba/Th, and U/Th but also emphasises the contribution of elements like HFSEs, REEs, olivine, and clinopyroxene in deciphering mafic magma sources.

The Alutaguse metavolcanics display a clear compressional arc tendency, as revealed by their REE patterns and elemental indices such as Y/15-La/10-Nb/8. This is further contrasted by the SS metavolcanics, which hint at a broader and transitional tectonic setting when analysed through the TiO_2–10(MnO)-10(P_2O_5) plot. The Hf/3–Th–Nb/16 triangular diagram accentuates their distinctions: Alutaguse gravitates towards crustal magma interactions, while SS leans towards subduction influences. Both, however, consistently show oceanic arc affinities as they align in the IAB zone. The Zr/Y values further distinguish them – Alutaguse samples explore both oceanic and continental realms, whereas SS samples remain largely continental. Nonetheless, their shared REE patterns and prominent placement in the IAB zone highlight mutual tectonic influences, indicating potential intersections in their tectonic histories (Kirs et al. 2009, Bogdanova et al. 2015, Soesoo et

al. 2020, Kara 2021). The resume of these associations is found in the Zr bivariant metavolcanic plots in Figure 3.

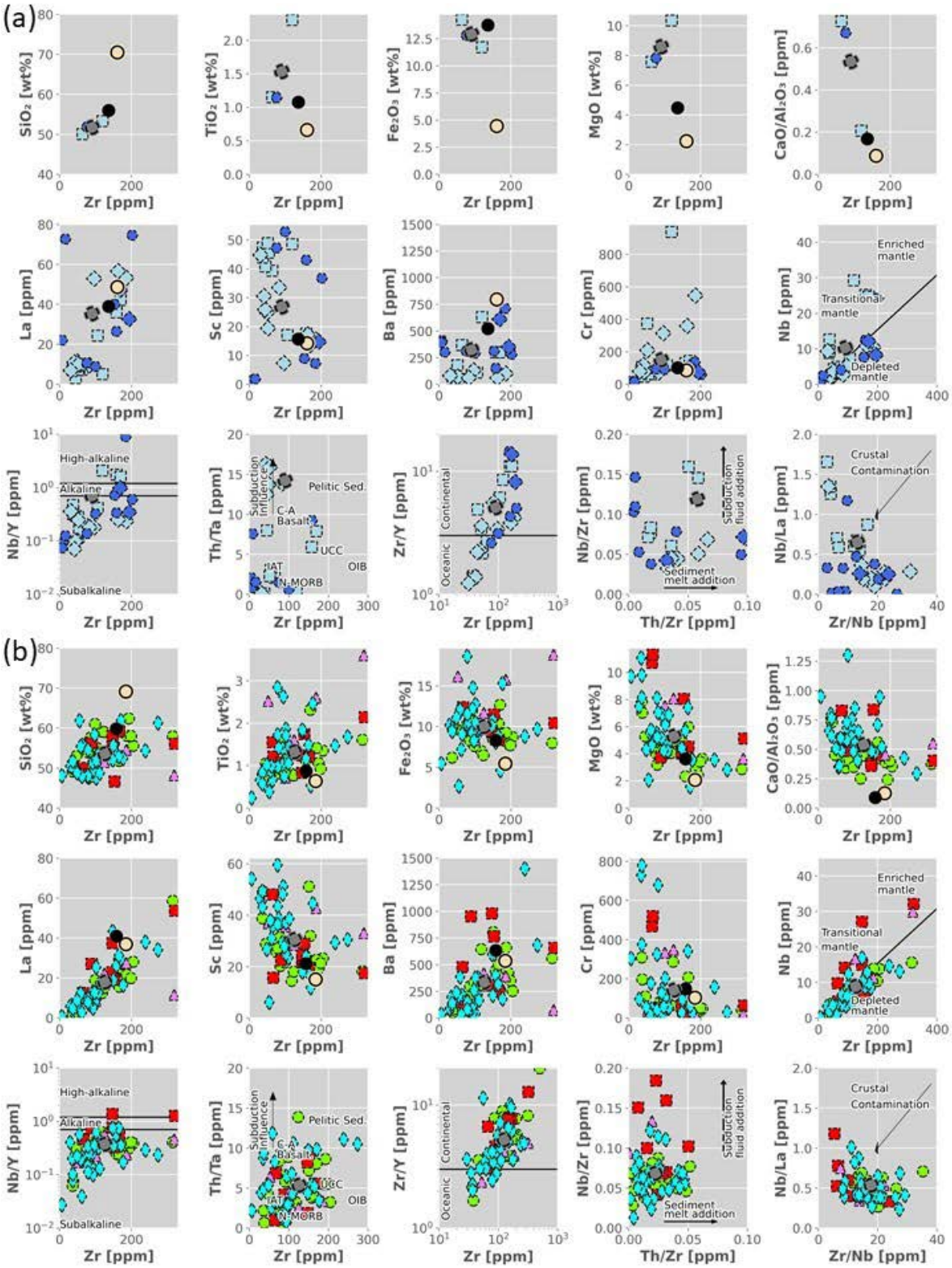

Fig. 3. Metavolcanic Zr binary plots versus major, trace and REE elements for a) Alutaguse and b) South Svecofennian (SS) zones. Legend as in Figure 2.

The Alutaguse metavolcanics display a clear compressional arc tendency, as revealed by their REE patterns and elemental indices such as Y/15-La/10-Nb/8. This is further contrasted by the SS metavolcanics, which hint at a broader and transitional tectonic setting when analysed through the TiO_2–10(MnO)-10(P_2O_5) plot. The Hf/3–Th–Nb/16 triangular diagram accentuates their distinctions: Alutaguse gravitates towards crustal magma interactions, while SS leans towards subduction influences. Both, however, consistently show oceanic arc affinities as they align in the IAB zone. The Zr/Y values further distinguish them–Alutaguse samples explore both oceanic and continental realms, whereas SS samples remain largely continental. Nonetheless, their shared REE patterns and prominent placement in the IAB zone highlight mutual tectonic influences, indicating potential intersections in their tectonic histories (Kirs et al. 2009, Bogdanova et al. 2015, Soesoo et al. 2020, Kara 2021). The resume of these associations is found in the Zr bivariant metavolcanic plots in Figure 3.

When juxtaposed, the Alutaguse and SS samples present a compelling tapestry of tectono-magmatic environments, revealing the complex interplay of geological processes. In conclusion, the evidence predominantly suggests that the Alutaguse and SS basins were situated in a continental arc setting. The SS basin appears to represent a subduction transference scenario, situated over a double subduction tectonic setting. Within this framework, the SS zones correspond to the northern subduction, while the Uusimaa and Tallinn Zones are aligned with the southern arc subduction process. Moreover, the Alutaguse basin might potentially represent a back-arc scenario if the Tallinn-Uusimaa Arc evolution system

REFERENCES

Bogdanova, S., Gorbatschev, R., Skridlaite, G., Soesoo, A., Taran, L. & Kurlovich, D. 2015. Trans-baltic Palaeoproterozoic correlations towards the reconstruction of the supercontinent Columbia/Nuna. Precambrian Research 259, 5–33

Kara, J. 2021. Evolution of the Svecofennian Bedrock in Southern Finland – Spatial and temporal changes in the mantle-derived magmatism and mantle-crust interaction. Doctoral thesis, University of Turku.

Kirs, J., Puura, V., Soesoo, A., Klein, V., Konsa, M., Koppelmaa, H., Niin, M. & Urtson, K. 2009. The crystalline basement of Estonia: rock complexes of the Palaeoproterozoic orosirian and statherian and Mmesoproterozoic calymmian periods, and regional correlations. Estonian Journal of Earth Sciences 58(4).

Soesoo, A, S. Nirgi, S. & Plado, J. 2020. The evolution of the Estonian Precambrian basement: geological, geophysical and geochronological constraints. Transactions of the Karelian Research Centre of the Russian Academy of Sciences (2), 18–33.

Solano-Acosta, J. D., Soesoo, A. & Hints, R. 2023. New insights of the crustal structure across Estonia using satellite potential fields derived from WGM-2012 gravity data and EMAG2v3 magnetic data. Tectonophysics, 846, 229656.

PROJECT VECTOR – RESEARCHING CHALLENGES TO MINING IN EUROPE THROUGH A ROBUST ETHICS STRUCTURE

by

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VECTOR (Vectors to Accessible Critical Raw Material Resources in Sedimentary Basins) is an EU Horizon and UKRI co-funded research project assessing the social, technical, and environmental challenges to mining critical raw materials in Europe. Our commitment to geoethics is informed by the diverse partnership's research expertise and our social science research. We have and will continue to incorporate these learnings into all research and outreach programmes, with the ambition of promoting good practice. Our dedicated ethics structure ensures that we put this commitment into action. This approach to project ethics is a first for a Horizon Europe project.

Plans for decarbonisation presented in the EU Green Deal include achieving Net Zero by 2050 and reducing net greenhouse gas emissions by at least 55% by 2030 (compared to 1990 levels). Meeting the supply of renewable energy needed to achieve these goals requires a sharp increase in production of, and a more responsible use of, critical raw materials. Recycling alone cannot meet the projected demand. Sourcing raw materials from inside the EU, where suitable environmental, social, and political regulations could be implemented, may be instrumental in securing an ethical provision of metals. However, mineral projects face complex social, environmental, and technical challenges in the EU. VECTOR will explore these challenges through social and geoscience research, integrating the results of both research streams into easy-to-understand resources.

The VECTOR consortium is committed to ensuring the highest level of ethical standards during the project, with respect to both conduct and outputs. To put this commitment into practice, the VECTOR consortium has appointed an Ethics Advisor, responsible for advising the project on ethical matters and Chairing an Independent Ethics Committee, which will bring subject matter expertise to ethical deliberations. The Ethics Advisor and the Independent Ethics Committee sit within an ethics governance framework that interacts with, but is independent of, the Project governance framework. This ensures that ethical matters arising during the Project are considered by expert and neutral third parties who are not otherwise directly invested in the Project, and that their advice is given due weight in Project decision-making processes and practically implemented. This is a novel approach for a Horizon Europe project, and one we hope will set the bar for strong ethical project management across the Horizon universe.

The approach will also be informed by our social science research, to consider how stakeholders balance the ethical, social, economic, political, and environmental consequences of sourcing critical raw materials. The aim is to understand how levels of social acceptance influence attitudes, decisions, and policy acceptance. Insights gained from this will inform good practice standards in our other research and be used to develop outreach tools accessible to all stakeholder groups, informing their future decision making. These include policy makers and the much-overlooked public, as well as continued professional development pathways for geoscientists.

Taken together, our ethics structure and social science research provide a robust geoethics framework that will evolve with our new understandings and inform our work to investigate a socio-environmentally sustainable supply of raw materials.

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