GREENPEG®

THE GREEN BOOK

Reflections on a European research project on securing raw materials for the energy transition

Table of Content

Foreword

Dear readers,

When the idea for the GREENPEG project was born in 2017, there was no talk of the EU Critical Raw Materials Act (CRMA). This year, when the CRMA came into force, the results of four years of research by the GREENPEG partners are now available for what the European Commission´s act also aims at: the strengthening of European exploration companies and geological surveys of the Member States.

With the decline in European mining for almost four decades now[1], a great deal of expertise in exploration, extraction and processing has been lost in Europe. If Europe wants to become more self-sufficient, it must compensate for its cost disadvantages - such as additional costs due to more extensive environmental regulations, higher personnel and operational costs, and a complex geological setting of the ore bodies - in the face of global competition. This can only be achieved through more innovation. That is why research is so important. However, these innovations "Made in Europe" must also be placed on the market. The ex-post evaluation of the EU Framework Programme for Research and Innovation Horizon 2020[2], within which GREENPEG was implemented, still sees insufficient market innovations in European research. GREENPEG stands for such market innovations as a result of a Research and Innovation Action, and the project's final results have tangibly furthered such innovations. It focuses not only on Europe, but also on the rapidly developing exploration projects in the large pegmatite provinces of Southern Africa and North America to qualify European exploration service providers and promote knowledge exchange both within Europe and beyond its borders. A total of six in-house seminars were held in Sweden, Austria, Portugal, Germany, Namibia and Norway and the results were presented at leading trade fairs and conferences in Finland, Canada and the USA.

The GREEN BOOK introduces into the many facets of GREENPEG, in which the partners not only committed themselves to the common idea of realising advances in making pegmatite exploration more efficient and environmentally friendly, but also to live the European spirit in terms of fostering European cooperation and social unity. This was expressed above all in the trans-European youth work with excursions and field work in Spain and Mozambique as well as a summer school in Norway. The exchange of views with the experts of tomorrow was important to us as well, with an extensive survey providing deep insights into the Generation Z's self-image and views on the European Green Deal. Furthermore, we learned more about the individual fate of a young Syrian who set off for Europe in a rubber dinghy to finally finish his geology degree in Germany. Will he one day practice his profession in Europe?
The GREEN BOOK also takes a look at the framework conditions for mining across the EU27, how they determine the feasibility of the EU CRMA in particular, and consider the role of mining in the context of a sustainability transformation. A guest article deals with the question

of the relocation of raw materials supply and examines its possibilities and limitations. A contribution on the Social License to Operate, which is a relatively recent phenomenon in Europe, is dedicated to the increasingly important topic of mining acceptance. Finally, this compilation of short essays presents the most important results of the GREENPEG project in individual articles and outlines the raw material potential of Scandinavia and its contribution to securing Europe's supply of raw materials.

With its rich illustrations, the articles in this issue provide an insight not only into the activities and results of the research, but also into the environment in which 13 partners from eight European countries worked over a period of four and a half years.

I wish you an interesting read.

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Freiberg, 31 October 2024

[1] C. Reichl, M. Schatz - World Mining Data 2024, Minerals Production, Federal Ministry of Finance, Republic of Austria, Volume 39, Vienna, 2024

[2] Ex post evaluation of Horizon 2020, the EU framework programme for research and innovation, Report from the commission to the European Parliament and the Council, {SEC(2024) 52 final} - {SWD(2024) 29 final} - {SWD(2024) 30 final}, Brussels, 29.1.2024

The emergence of the GREENPEG project idea

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The GREENPEG project was a research and innovation action (RIA), funded by the European Commission's Horizon2020 program and implemented from 2020 to 2024. It aimed to develop and implement new and advanced exploration techniques for identifying and characterizing pegmatite type deposits. Pegmatites are small-scale (0.01-5 million m^3) rock/ore bodies which may contain the commodities lithium, tin, tantalum, niobium, beryllium, caesium, rare earth elements, high purity quartz, mica, feldspar, kaolin and gemstones (beryl, tourmaline, topaz, etc.) in economic quantity. By improving the understanding of the geological and geochemical characteristics of these important deposits of a number of critical and strategical raw materials (CRM/SRM), the project seeked to facilitate the discovery and sustainable extraction of especially those CRM/SRM needed for the transition to a low-carbon economy, particularly lithium, high purity quartz for silica and metallic silicon, ceramic feldspar, rare earth elements, tantalum, beryllium and cesium. As such, the GREENPEG Horizon2020 project contributes in supporting the European Union's efforts to secure a sustainable supply of CRM/SRM for green energy technologies and promoting the transition to a more environmentally friendly and resource-efficient economy. By its research approach it aimed at reducing the environmental footprint of surveying and saving costs at all stages of exploration from reconnaissance to detailed exploration.

The project idea and development had its origin in the Norwegian Centre for Mineralogy (NORMIN) at the Natural History Museum of the University of Oslo (UIO). Being a forefront institution in raw material research and economic geology, the development of the GREENPEG project is in line with the long tradition of bringing raw material research into the application for the benefit of the society. The tradition started with the establishment of the Kongsberg School of Mines in 1757 as one of Europe's earliest educational institutions for higher education in mining engineering. In 1814, the school was integrated in the newly founded UIO. In 1917, Victor Moritz Goldschmidt (1888 -1947) established the first State Raw Material Laboratory (*Statens Råstofflaboratorium*) at UIO, with the goal to find alternative minerals so that Norway could become less independent on the international market of conventional raw materials during the First World War. Today, Goldschmidt's inventions and ideas about raw materials are more relevant than ever in a time of technological transition to the production of green energy in a geopolitical tense time.

The decision to implement the GREENPEG project at European level as a Research and Innovation Action (RIA) arose in 2017 when it was first realised that exploration experience and methods for pegmatites were basically lacking. This was the time of increasing interest in pegmatite exploration as the main hard rock source for lithium and high purity quartz. The general failure of conventional exploration methods is due to the nature of pegmatite ore bodies, which are relatively small, their indistinct geophysical responses, and our relatively poor understanding of petrophysical and chemical-mineralogical properties, including the complex textural, mineralogical and chemical variability of pegmatites and their country rock halos. Particularly important for the initiation of the GREENPEG project were two research outcomes of the NORMIN group. First, that quartz can be utilised as pathfinder mineral for exploration of mineralised pegmatites (Müller et al., 2015) and second that pegmatites form not necessarily from residual melts of granite plutons but may be also generated directly by partial melting (anatexis) of metamorphic rocks (Müller et al., 2017). The first finding was later implemented as a tool of the GREENPEG exploration toolset and the second finding resulted in extended genetic model of pegmatite formation as part of the GREENPEG mineral system approach for pegmatite exploration.

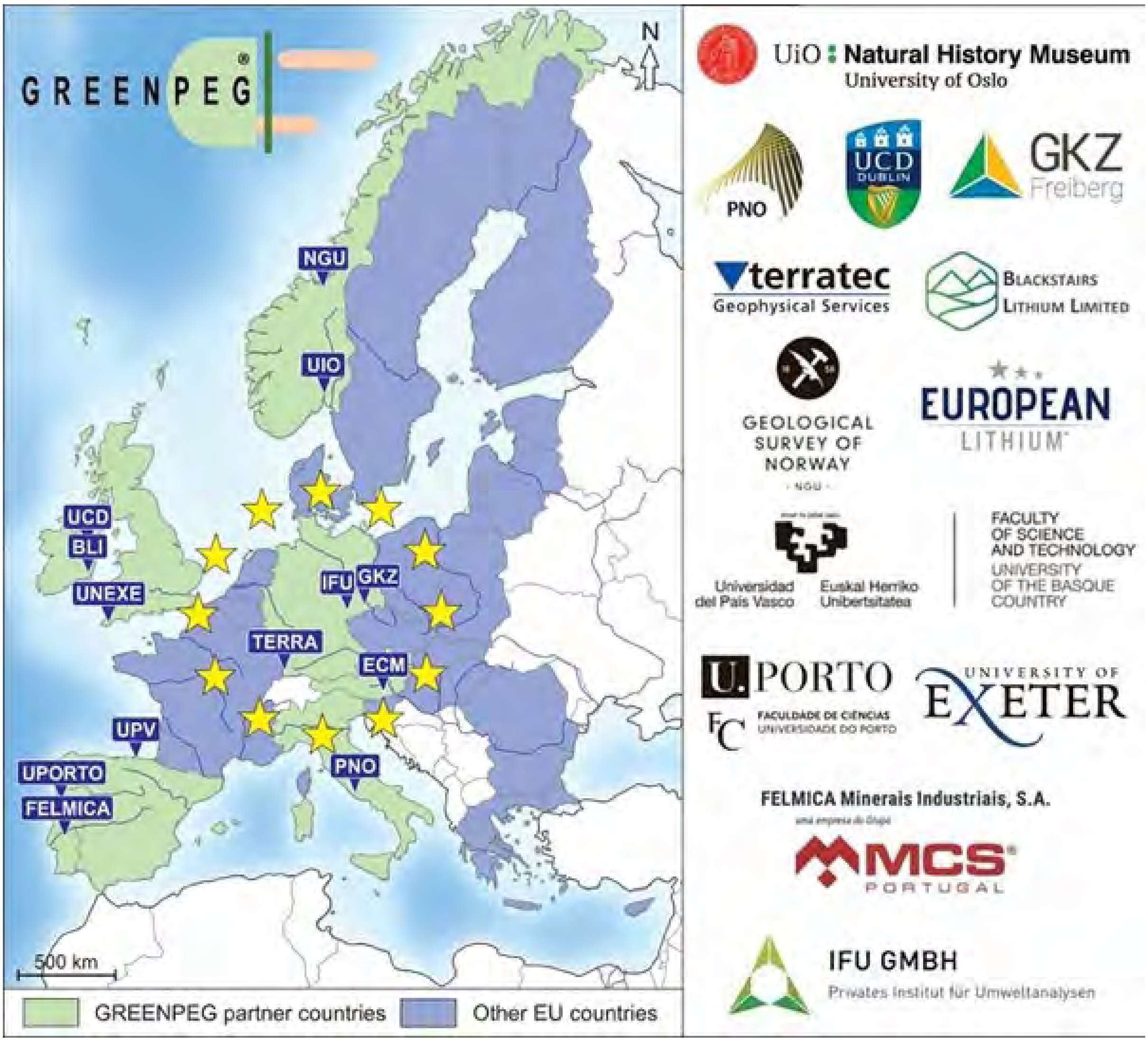

Figure 1: Map of Europe with headquarters of GREENPEG partners: UIO – Natural History Museum of the University of Oslo, UCD - University of Dublin, TERRA - terratec Geophysical Services GmbH, GKZ - Geokompetenzzentrum Freiberg e.V., BLI - Blackstairs Lithium Ltd., NGU - Geological Survey of Norway, IFU - Institut für Umweltanalysen GmbH, UPV - University of the Basque Country, UNEXE - University of Exeter, ECM - ECM Lithium AT GmbH , UPORTO - University of Porto, FELMICA - Felmica - Minerais Industriais, S.A., PNO - Ciaotech - PNO Group.

From 2017 on, the project idea was extended and formulated in cooperation with the University of Exeter, University College Dublin, University of Porto, and University of the Basque Country, the exploration services/mining operators terratec Geophysical Services GmbH & Co KG, Felmica - Minerais Industriais, S.A., Blackstairs Lithium Ltd., IFU GmbH, and ECM Lithium AT GmbH, the Geological Survey of Norway, the non-profit association Geokompetenzzentrum Freiberg e.V. (GKZ), and the business consultant Ciaotech - PNO Group (Figure 1). They all have been working on research and innovation in order to valorise EU mineral wealth in course of the European Innovation Partnership on Raw Materials which was launched by the European Commission in 2012. The project application was finally accepted and funded by the European Commission in 2020.

GREENPEG at a glance

Project aim

GREENPEG has developed and validated a new multi-method toolset to explore for buried, rare metal and high purity quartz pegmatites. Individual tools were tested in three active European pegmatite exploration areas exposing different surface environments and topography to also apply new approaches of remotely sensed data: Wolfsberg in Austria (alpine, wooded), Leinster in Ireland (temperate forest), and Tysfjord in Norway (coastal Arctic) (Figure 2). The selection of the GREENPEG demonstration sites spans the spectrum of challenges in exploration for European pegmatite deposits, such as variable wall rocks (Leinster), dense vegetation (Norway), extreme (alpine) topography (Wolfsberg), thick soil cover (Leinster); features which ensure that the delivered toolset is robust and flexible enough to be applicable in manifold environments.

Figure 2: Field images of the three demonstration sites illustrating different European conditions (topography, vegetation, soil cover, climate, inhabitation) and outcrops of mineralised pegmatites for verification of the GREENPEG toolset.

Approach

The GREENPEG choice of geophysical and geochemical methods comprising the toolset is based on a well-designed strategy depending on the specific characteristics of the pegmatite ores and focuses on targets in commercial surveying as well as territorial mapping by surveys:

1. low contrast of petrophysical properties compared with their wall rocks;
2. high mineralogical variability within and between different pegmatite types;
3. specific magnetic properties and radioactivity of pegmatite-forming minerals;
4. relatively small ore body volumes (0.01–5 million m^3/0.025–12.5 million tonnes) and lateral extent;
5. the occurrence of pegmatites in clusters (fields); and
6. the existence of lithochemical halos of lithium, rubidium, cesium and thorium, uranium at a scale of 1 to 50 m around pegmatite bodies.

The second foundation of toolset development is the new multilevel approach: province scale (500–10 000 km^2), district scale (25–500 km^2) and prospect scale (<25 km^2) (Figure 3). Each scale approach combines several technological innovations to produce integrated solutions. The province-scale methodologies comprised the processing of accessible Landsat-8, Sentinel-2 and ASTER satellite images by applying new red–green–blue combinations, band ratios and subsets for principal component analysis, satellite radar images (Sentinel-1) and airborne LiDAR (light detection and ranging) data for topographic mapping of province-scale tectonic structures (faults), which potentially controlled pegmatite melt emplacement. The GREENPEG district-scale methodology included airborne high-resolution gamma-ray radiometry, magnetometry and electromagnetics with a flight-line separation of 30–50 m and an elevation of 30–50 m above ground, adapted to the small size of pegmatite ore bodies and clusters.

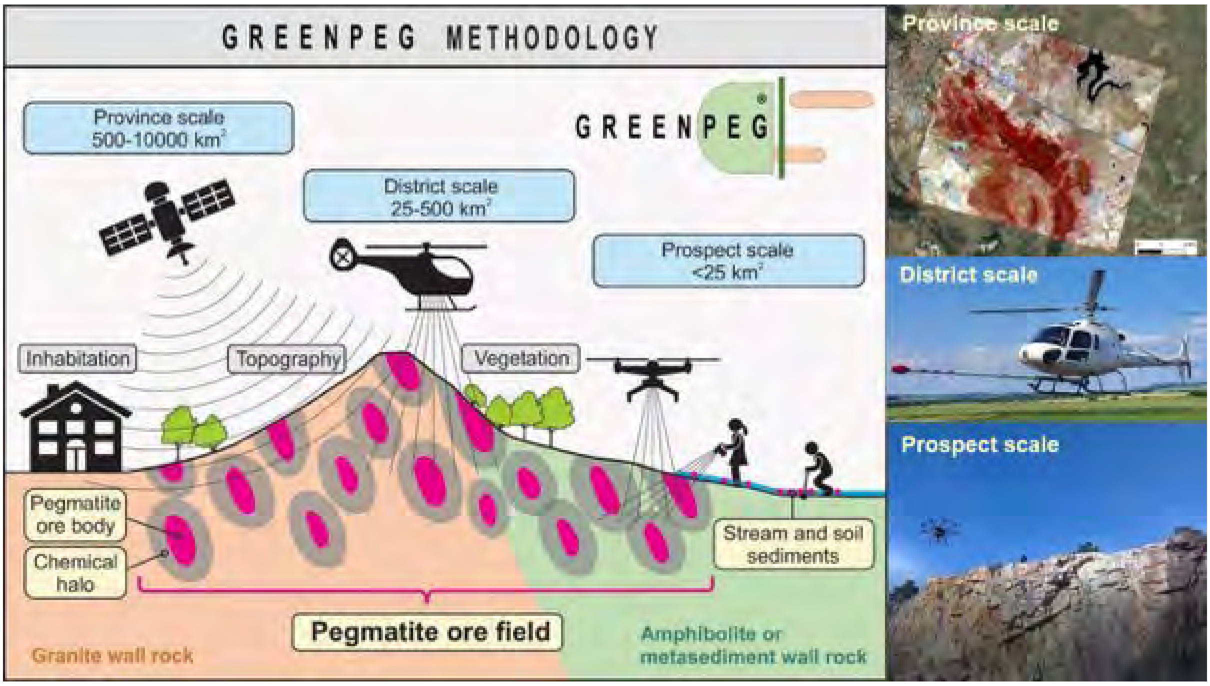

Figure 3: Schematic sketch of exploration methodologies applied in GREENPEG for buried, small-scale pegmatite ore bodies at province, district and prospect scale (Müller et al. (2022).

For prospect-scale exploration, combinations of an instrumental heavy-duty drone, a magnetometer, gamma-ray and hyperspectral spectrometers and a ground-based piezoelectric seismograph have been developed and tested. Stream and soil sediment sampling and analysis, whole-rock lithochemical, portable X-ray fluorescence, portable laser-induced breakdown spectroscopy and scintillometer wall rock halo mapping, and trace-elements-in-quartz mapping allowed vectoring to areas with the highest ore potential and quality. Together with surveys of ground-based ground-penetrating radar, high-resolution gravimetry and two-dimensional resistivity/induced polarization integrated modelling, this delivered high-resolution three-dimensional maps of pegmatite ore bodies at a depth of up to 100 m.

Responsible exploration

GREENPEG work plan incorporates a careful analysis of environmental, social and safety impacts within the implementation of the new technological approach, assessing these aspects through the entire life cycle of exploration techniques being developed and sharing best practices in these spheres among partners, industry bodies and international research projects. This in turn will bring GREENPEG closer to the UNCF targets and in consequence in line with the EU Critical Raw Materials Act and the EU GREEN DEAL.

The consortium

The GREENPEG consortium is a well-balanced, multi-disciplinary, pan-European team of eight industry and five research and academia partners from eight different European countries including three mine developers and three exploration companies to meet the objectives of this project (Figures 4 to 6). The GREENPEG team links in a highly complementary manner all the expertise and competence necessary for the development, upscaling and validation of multi-method toolsets for European pegmatite ore exploration.

A business consultancy and a triple helix raw materials cluster were in charge of the exploitation of the results, networking, preparation of the business plans, and measures to raise raw material awareness to link up with civic society and administration. The primary choice of the research partners is based on the fact that Norway, Austria, Ireland, Portugal, and Spain host the largest number of active pegmatite mines and/or exploration sites in Europe and, thus, have the highest exploration potential for futures deposits. All mentioned countries are engaged in the research about their resource potential of raw materials and how the European Union is going to valorise its mineral wealth.

The GREENPEG project was managed and coordinated by an experienced team at the Natural History Museum of the University of Oslo, with Axel Müller as the scientific coordinator and Carla Pueyo Lloret as the project manager.

Carla Pueyo Lloret, the GREENPEG project manager, said in an interview:

"*Having always been passionate about geology, I became particularly interested in mineral deposits and economic geology during the fourth course of my Geology Engineering degree when I visited several mines in the Iberian Pyrite Belt in the South of Spain. During the more than ten years as Project Manager I have been lucky to work in fascinating research and innovation projects in the extractive industry.*
Along these experiences, I enjoyed working in collaboration with a wide range of stakeholders, ranging from industry members and consultants, scientists, government agencies and NGOs. When the opportunity to manage GREENPEG presented, it was a no brainer for me. The chance of finding innovative and sustainable solutions to explore and discover green-tech minerals while working closely with international experts in the field of pegmatites sounded very fun and exciting. It has been an absolute wonder working with the international professional individuals of the GREENPEG Consortium for the past four and a half years. We have not only achieved unique results, but also built very strong cooperation and professional relationships which I am sure will continue to flourish in future projects. We are proud of our intense collaborative work dedicated to address exploration, one of the significant challenges along the raw materials value chain."

Axel Müller, the GREENPEG coordinator, said in an interview:

"The establishment and coordination of the GREENPEG project has been the most rewarding, enjoyable, and challenging achievement of my profess-sional career. The success of the project is, of course, a result of the dedication and hard work of all the colleagues and partners involved in its setup and execution. It has been a unique and formative experience to witness how the combined knowledge of scientists and engineers with diverse expertise can create methodologies and technological innovations, and transformthem into practical applications in a relatively short period.
Born in the historic and then-active mining region of Saxony, Germany, and with an engineering geologist as a father, mining and geology shaped my childhood. As a logical result, I became a geologist. Early in my career, I developed a keen interest in discovering which raw materials are used to make everyday items, how these materials form in nature, and where they can be found. With the GREENPEG project, a dream has come true: transforming research into practical applications for the benefit of society by developing methods to find critical raw materials essential for the green transition.

Figure 4: Partners of the GREENPEG project consortium including members of the GREENPEG Advisory Board and Think Tank enjoying, after an intense day of meeting, a visit to the Jardim Botânico do Porto, Portugal in October 2022.

Figure 5: Members of the GREENPEG project consortium, Think Tank and Advisory Board at the Königstein Fortress during the first Exploitation Seminar of GKZ in Dresden, Germany, in May 2022.

Figure 6: Partners of the GREENPEG project consortium enjoying a visit of Leipzig town centre and dinner after the second Exploitation Seminar in Leipzig, Germany, in October 2023.

Key findings

The core result of the GREENPEG project is an integrated, multi-method toolset for exploration of buried pegmatites. The exploration toolset can be tailored to the geology and broader characteristics and challenges of the targeted exploration area, as well as specific customer needs in terms of goals, level of experience and budget. Individual tools or tool combinations of the toolset can be used to vector towards buried pegmatite-related mineralization to maximize the success of subsequent more costly exploration such as drilling in ways that optimize environmental, social and governance outcomes.

Beside adjusted conventional and newly developed exploration methodologies, the results comprise novel data processing approaches and three new geophysical exploration devices:

1. EASA-certified, helicopter-compatible nose stinger magnetometer/radiometer,
2. piezoelectric seismograph,
3. drone-borne hyperspectral system, and
4. two specialist, open-access databases:
    a) spectral library of pegmatites, pegmatite minerals and pegmatite host rocks accessible on https://doi.org/10.5281/zenodo.6518319
    b) petrophyiscal database for pegmatite ores and host rocks accessible on https://doi.org/10.5281/zenodo.7347371.

The toolset is designed so that both experienced exploration companies and regional surveys can apply individual tools or method combinations independently, following the guidance provided in the toolset publication (Müller et al., 2024, in review), or, if advice or method-performance help is required, the user may contact one of the GREENPEG partners.

Educating the new generation of exploration geologists and raising raw material awareness of multiplicators and political decision makers of the civic public and administration

In the course of the project, GREENPEG carried out measures to enhance the raw material awareness among multiplicators from the civic public, policymakers, and the administration through a combination of activities, which involved education, dialogues with mine developers, administration and those affected by mining projects, and providing representatives of the civic public insights into the raw materials ecosystem.
In order to introduce young careers into the subject and how mining contributes to the energy and green transition, GREENPEG carried out a one-week excursion in Spain with students studying energy engineering and social sciences with comparatively little knowledge about the raw materials sourcing. The aim was to practically introduce them into the generation of renewable energies (wind, solar, hydro and wave power plants) and the respective extraction sites of those raw materials needed to set up such plants (Figure 7). The students were also made familiar with the environmental foot print and CO_2 emissions of both, the mines and the power plants, as well as its surface consumption.

Figure 7: The participants of the GREENPEG students excursion in front of a 3MW storage unit at Iberdrola Arañuelo solar farm. How much lithium ore had to be mined to supply the battery grade lithium for the 3MW storage unit?

Furthermore, GREENPEG implemented three Focus Group Meetings targeting different stakeholder groups to introduce them into the aim and objectives of the GREENPEG project and into the framework conditions of valorising the European mineral wealth. At the Koralpe lithium exploration mine in Styria, Austria, science journalists, politicians and administration from permitting authorities were introduced into the challenges of setting up a mine in Europe and how foreign investors regard the EU policy in terms of unlocking Europe's mineral wealth (Figure 8). These efforts aimed also to promote sustainable raw material sourcing, to discuss challenges in raw material policy-making, and advocate for best ESG practices in exploration in line with the economic viability of exploration and mine projects in Europe.

Figure 8: Members of the Young Greens during their site visit of Koralpe lithium exploration mine at Wolfsberg, Styria.

Another education measure was the GREENPEG Student Summer School at Tysfjord in northern Norway in June 2023 (Figure 9). During the two-week field course, advanced students of the natural sciences who want to work in minerals exploration from eight European countries were taught the GREENPEG toolset and distinct exploration techniques. The GREENPEG team introduced the students into responsible exploration practices aiming at minimizing negative environmental and social impacts. They also provided insights to better understand the mining business and entrepreneurial decision-making, particularly in the context of investing in the EU raw materials ecosystem in the given global framework conditions. In the course of the GREENPEG Students Summer School, a number of public awareness campaigns and community engagement events were carried out, such as the GREENPEG Open Day at the Árran Lule Sami Centre in Drag at Tysfjord. The local community was invited to learn more about the GREENPEG project and to learn each other better.

Figure 9: Participants of the GREENPEG Summer School in Tysfjord, Norway, June 2023.

Outlook

After the project ends in October 2024, members of the project consortium will continue to work as the GREENPEG Expert's Network ensuring the exploitation and dissemination of the toolset, marketing products as well as providing advice to stakeholders in the long term. The network will be an advisory and service-providing group not operating as a corporal entity. It aims to commercialise the expertise and technological innovations gained and developed during the GREENPEG project by its given statutes. Information and advertisement of services will be accessible through the GREENPEG Expert's Network website, such as packages of tools and expertise or individual method offered by each partner or combination of partners, together with their contact information. In this regard, the GREENPEG digital presence will continue under www.greenpeg.eu. The group will promote sourcing of resources from pegmatite-type deposits for industrial use and manufacturing in Europe, but not limited to European resources as per the original GREENPEG proposal.

References

Müller A., Ihlen P.M., Snook B., Larsen R., Flem B., Bingen B., Williamson B.J. (2015) The chemistry of quartz in granitic pegmatites of southern Norway: Petrogenetic and economic implications. Economic Geology 110: 1737-1757. https://doi.org/10.2113/econgeo.110.7.1737

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

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. Geological Society, London, Special Publications 526: 193-218. https://doi.org/10.1144/SP526-2021-189

Müller, A., Brönner, M., Menuge, J., Williamson, B., Haase, C., Tassis, G., Pohl, C., Brauch, K., Saalmann, K., Teodoro, A., Roda-Robles, E., Cardoso-Fernandes, J., Smith, K., Wall, F., Lima, A., Santos, D., Hopfner, M., Garate-Olave, I., Errandonea-Martin, J., Harrop, J., Carter, L., Keyser, W., Zhou, H., Nazari-Dehkordi, T., Geiger, E., Unterweissacher, T., Steiner, R., Reimer, W., Pueyo Lloret, C. (2024) The GREENPEG project toolset to explore for buried pegmatites hosting rare metals and high purity quartz. Economic Geology (in review).

Sourcing and Policy Making

Pointing on a spodumene crystal in mineralised pegmatite outcrops at ECMs´ Koralpe exploration mine

Walk the line: Cooperation and Competition in the Critical Minerals Sector

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Recent events have highlighted that interdependencies in global supply chains come with risks that can threaten their resilience. The COVID-19 pandemic revealed how supply chain disruptions can cause significant production delays and losses, and Russia's war against Ukraine exposed Europe's dependence on Russian gas. Political decision-makers in Europe have derived a key lesson from these incidents: the vulnerabilities resulting from high interconnectedness and dependencies shall be addressed by building strategic autonomy in important supply chains and sectors. At the same time, the window of opportunity to keep global warming within tolerable limits is narrowing and the need to decarbonise the global economy is becoming ever more apparent. The minerals and metals needed for the twin transition—comprising the digital and green transition, including renewable energy deployment and decarbonization of high-pollution sectors—as well as for certain defence and space applications, are largely sourced from countries in the Global South. While many minerals and metals are available in sufficient quantities, the long lead times from discovery to production—averaging 16 years and increasing (Manalo, 2024), although significantly shorter for some raw materials—combined with the urgency of rapidly transitioning to low-emission technologies leads to competition for various resources such as rare earths, platinum group metals, nickel, cobalt, and lithium.

In addition, there is a significant geopolitical dimension to consider. China's dominant position in both the extraction and processing of many of these resources is considered particularly problematic, as concerns grow that those strategic raw materials and related technologies could be weaponized for political interests. This concern is underscored by China's recent export restrictions on gallium and germanium (since August 2023), high-grade graphite (December 2023) and rare earth processing technology (January 2024). Embedded in the larger systemic rivalry between the US and China, the role of geopolitics in the global “race for critical minerals” is hence gaining prominence.

Policy responses in industrialized countries: securing supply and reducing dependencies

In response to these developments, two main policy approaches have emerged. On one side, industrially strong regions with low mining capacities are employing industrial policy programs to develop strategic supply chains domestically and among friendly states (friendshoring) and seek to diversify their supplier networks. On the other side, resource-rich countries are seizing the opportunity to move beyond their status as exporters of unprocessed raw materials and promote the establishment of processing and manufacturing capacities within their own borders, thereby increasing local value creation and open pathways for industrialization.

Multiple industrialized countries and regions that are highly dependent on imports of minerals and metals for their industrial manufacturing and production, including the EU, Japan, South Korea, Australia, and the US, have published lists of "critical" or "strategic" raw materials for several years—those considered important regarding economic and security concerns for key technologies, coupled with high import dependencies and supply risks. The resurgence of industrial policy promoting multiple stages of the supply chain, from extraction to refining and manufacturing, is a more recent phenomenon. Examples include the US Infrastructure Investment and Jobs Act, which provides funds for extracting critical minerals, initiating pilot processing projects, and supporting research efforts; as well as the US Defence Production Act whose scope was expanded by President Biden to boost domestic innovation and supply of several key minerals vital for electric vehicle battery production. The US Inflation Reduction Act (IRA) from August 2022 provides around USD 370 billion in state funding for programs aimed at curbing inflation, advancing the green transition, and relocating key industries to the US. It offers a 10% tax break to companies extracting critical minerals within the US while currently 50% of the market value of critical minerals used in EV batteries must come from domestic extraction or from supplier countries with which the US has a free trade agreement (FTA) – increasing to 70% for 2026 and 80 % after that.

The EU's response to the IRA includes the Net-Zero Industry Act (NZIA) and the Critical Raw Material Act (CRMA), the latter setting benchmarks for the extraction (10%), processing (40%), and recycling (25%) of strategic minerals within Europe (Schulze, 2024). Moreover, it foresees that only 65% of the EU’s demand for each of the 17 raw materials considered strategic may be sourced from a single third country.

Both policy programs aim to establish alternative raw material supply chains independent of China. They are supported by initiatives such as the Mineral Security Partnership (MSP), a consortium of 14 countries (as of June 2024) and the EU, aiming to develop diverse and sustainable mineral supply chains through joint strategic projects along the value chain. At the same time, Canada and Australia, both resource-rich and industrialized countries, are seeking to reduce the dominance of Chinese actors in their domestic mining sectors. The Canadian government now assesses foreign investments in critical raw materials projects and only allows major acquisitions in exceptional cases. Recently, three Chinese companies were forced to sell their stakes in two Canadian lithium firms, and the government blocked the Chinese company Shenghe from acquiring stakes in Canada's only rare earth mine (Carry, 2024). At the moment, many new investments are concentrated in a few resource-rich countries that are considered as reliable partners with favorable conditions, e.g. Canada and Chile (Castro and Brucal, 2024). Other countries with large mineral deposits are at risk of falling by the wayside. Yet countries in different world regions should be taken into account for several reasons: to mitigate the risk of over-reliance on a few key suppliers; to counter-balance the influence of China; and to foster economic growth and capacity building in the respective countries. Moreover, investments in exploration projects in these countries may increase global mineral availability and thus help alleviate future supply bottlenecks. The EU's current strategy, however, tends to be rather cautious and depends on private sector involvement as it lacks an own raw materials agency or EU-owned mining companies. This has led to lower investment levels in many mineral-rich areas, like Latin America and southern Africa, compared to the investments made by actors such as China, the UAE or Saudi Arabia.

Strategies of resource-rich countries in the Global South

Despite these developments, the high resource demand of industrialized nations places resource-rich countries nevertheless in the good position to be able to choose their partners in the raw materials sector. The range of policies employed by resource-rich countries to capitalize on this opportunity extends from export restrictions (e.g., Zimbabwe, Namibia, Indonesia, Malaysia), increasing taxes and royalties (e.g., Argentina, Chile, Tanzania, Zambia), nationalization of critical resources (e.g., Mexico, Zambia, Zimbabwe), to contract renegotiations with mining companies (e.g., DRC, Mongolia, Peru) (van Halm, 2023). According to an OECD analysis, worldwide export restrictions on critical raw materials - particularly on ores and minerals - increased significantly in the period 2008-2020 (Kowalski and Legendre, 2023). About 10% of the global export value of critical raw materials was subject to at least one export restriction in 2020, most commonly export taxes. While quantitative export restrictions are mostly prohibited under WTO rules, some resource-rich countries see this as the most promising strategy to stimulate foreign and domestic investment in the processing industry.

One case in point is Indonesia, which started banning the export of several unrefined minerals as early as 2014. Although this strategy has proven to be a fast way to expand the processing capacity in Indonesia – with nickel-related exports rising from USD 6 billion (2013) to almost USD 30 billion nine years later (Abdurrachman, 2023) - it also raised international criticism, including a complaint at the World Trade Organization (WTO) filed by the EU alleging that this practice breaks free trade rules. Moreover, it does come with several drawbacks, such as heightened dependency on Chinese actors, knowhow, and equipment; economic losses in the short term; and significant environmental and social costs (Tritto, 2023). Also, this approach is rather difficult to replicate for other resource-rich countries and often depends on the economic context, as the extent to which a country may actually be able to incentivize companies to invest in processing facilities or further manufacturing mainly depends on the global supplier landscape as well as the technological potential to substitute a certain mineral or metal.

Chile, on the other hand, employs a more modest approach regarding the exploitation of lithium: The National Lithium Strategy from April 2023 aims to attract FDIs in the lithium sector by providing economic incentives like preferential lithium prices for companies that invest in value-added projects. Furthermore, it foresees the creation of a National Lithium Company, which shall in the future exploit lithium reserves in public-private partnerships (PPPs) with a majority share in the Salar de Atacama and Maricunga, where lithium concentrations are considered highest. Other salt flats may also be exploited by private companies alone. At the same time, Chile is reinforcing its raw material cooperation to support the establishment of its downstream sector, for instance with Germany and the EU, and signed a Memorandum of Understanding for the establishment of a “Binational Lithium and Salt Flats Working Group” with Argentina (MercoPress, 2023).

Conclusion

It is still too early to assess the effects of the strategies employed by resource-rich countries regarding their potential to foster industrial growth, and concerning any adverse impacts on global minerals trade. Furthermore, current developments are jeopardizing the global objective of sustainable development. To counteract this, two points should be considered.
First, countries that are dependent on imports of minerals and metals must balance the urgency to act swiftly – as Chinese companies have been investing in resource projects around the world in unprecedented speed – with the need to uphold environmental, social, and governance (ESG) standards, and delivering on their promises of value addition to be perceived as reliable partners in resource extraction. In practice, this means that efforts to build up domestic supply chains must be carefully weighed against the justified demand of resource-rich countries to build up their own industrial capacities.

Second, the extraction of minerals required for clean energy technologies inevitably entails adverse social and ecological effects. To mitigate these impacts, resource-demanding countries must not only adhere to ESG standards but also invest in complementary measures such as circular economy programs and recycling initiatives to reduce the negative consequences of primary extraction. Furthermore, reducing the overall demand for resources should be recognized as a fundamental pillar for enhancing economic resilience, as it helps to alleviate strategic vulnerabilities associated with import dependencies. By prioritizing these strategies, countries can promote sustainable development while minimizing the ecological footprint of their clean energy transitions. Acknowledging the environmental and social burdens that resource-rich countries have borne in the past underscores the necessity of developing a resource strategy that ensures a more equitable distribution of resources and aligns with the world's common goal to limit climate change.

For a more detailed version of this article please see:

Carry, Inga; Müller, Melanie and Strack, Lea (2023): *Running the race for critical minerals – between geopolitical rivalries and sustainable development*. In: Research Network Sustainable Global Supply Chains: Sustainable global supply chains in times of geopolitical crises. Annual Report 2023. Berlin: Stiftung Wissenschaft und Politik (SWP), p. 58-87. https://www.sustainablesupplychains.org/wp-content/uploads/2024/01/SustainableGlobalSupplyChains-Report2023.pdf

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References

Abdurrachman, F. (2023, September 28). Assessing nickel downstreaming in Indonesia. *East Asia Forum*. https://www.eastasiaforum.org/2023/09/28/assessing-nickel-downstreaming-in-indonesia/

Castro, L., & Brucal, A. (2024, June 05). The unintended consequences of investment policy on critical minerals investment. World Bank Blogs. https://blogs.worldbank.org/en/psd/critical-mineral-investments

Carry, I. (2024): Rohstoffpartner Kanada: ein (nahezu) perfekter Match. Die europäisch-kanadische Rohstoffkooperation in Zeiten des friendshoring. SWP-Aktuell 2024/A27. https://www.swp-berlin.org/publikation/rohstoffpartner-kanada-ein-nahezu-perfekter-match

Kowalski, P., & Legendre, C. (2023). Raw Materials Critical for the Green Transition: Production, International Trade and Export Restrictions. OECD Trade Policy Paper No. 269. https://www.oecd-ilibrary.org/docserver/c6bb598b-en.pdf?expires=1720019536&id=id&accname=guest&checksum=756D9B5BD0632A81F8011327EC9A6D67

Manalo, P. (2024, April 10). Average lead time almost 18 years for mines started in 2020–23. S&P Global. https://www.spglobal.com/marketintelligence/en/news-insights/research/average-lead-time-almost-18-years-for-mines-started-in-2020-23

MercoPress (2023, November 11). Argentina and Chile sign key lithium agreement. https://en.mercopress.com/2023/11/11/argentina-and-chile-sign-key-lithium-agreement

Riofrances, T., Kendall, A., Dayemo, K., Haugen, M., McDonald, K., Hassan, B., Slattery, M., & Lillehei, X. (2023). Achieving Zero Emissions with More Mobility and Less Mining. Climate and Community Project. http://www.climateandcommunity.org/more-mobility-less-mining

Schulze, M. (2024): Security of Supply in Times of Geo-Economic Fragmentation. Enhancing the External Dimension of the EU's Raw Materials Policy. SWP Comment 2024/C15 Security of Supply in Times of Geo-economic Fragmentation - Stiftung Wissenschaft und Politik

Tritto, A. (2023). How Indonesia Used Chinese Industrial Investments to Turn Nickel into the New Gold. Carnegie Endowment for International Peace. https://carnegieendowment.org/research/2023/04/how-indonesia-used-chinese-industrial-investments-to-turn-nickel-into-the-new-gold?lang=en&center=global

Van Halm, I. (2023, January 19). Zimbabwe joins the wave of resource nationalism. *Mining Technology*. https://www.mining-technology.com/features/zimbabwe-critical-minerals-resource-nationalism/?cf-view

Ask ChatGPT

Question posed on 23rd October 2024

What are the weaknesses of the EU Critical Raw Materials Act in terms of its feasibility?

The EU Critical Raw Materials Act (CRMA), proposed in 2023, aims to secure a sustainable supply of critical raw materials (CRMs) for Europe's green and digital transitions. While the act is ambitious in reducing dependence on imports and increasing EU production, there are several weaknesses in terms of its feasibility:

1. Supply Chain Constraints

- **Limited Domestic Resources**: The EU has a relatively small geological endowment of many critical raw materials, such as rare earth elements (REEs), lithium, and cobalt. Identifying, assessing, and developing new mining projects within Europe could take years or even decades. This challenges the goal of sourcing 10% of the EU's critical raw materials domestically by 2030.
- **Competition for Global Resources**: Europe faces stiff competition from other major players, particularly China and the U.S., which have long-established supply chains and processing capacities for CRMs. This global race for materials could hamper the EU's ability to secure imports and develop diversified supply chains.

2. Bureaucratic and Regulatory Hurdles

- **Lengthy Permitting Process**: Mining and refining projects in the EU are subject to stringent environmental regulations and lengthy permitting processes. Developing a mine in Europe can take more than a decade, which conflicts with the CRMA's 2030 timeline. Local opposition to mining and environmental concerns are also significant obstacles.
- **Coordination Among Member States**: The CRMA requires coordination between EU member states to identify and develop strategic projects, but there may be differences in priorities, regulatory frameworks, and local interests. Achieving uniform regulatory and financial support across all member states could be a slow and politically challenging process.

3. Technological and Infrastructure Challenges

- **Limited Processing Capacity**: The EU lacks sufficient refining and processing capabilities for many critical raw materials. Building processing plants is capital-intensive and time-consuming, and the EU would need to develop new technologies and infrastructure to process these materials sustainably and efficiently.
- **Innovation Gaps**: While the CRMA encourages recycling and innovation in CRM substitution, current technologies for recycling critical raw materials like lithium or

rare earth elements are either costly or not fully developed at scale. The feasibility of rapidly scaling up these technologies by 2030 remains uncertain.

4. High Dependence on Imports

- **Dependence on Non-EU Suppliers**: Despite efforts to diversify supply chains, the EU will remain heavily dependent on imports from non-EU countries, particularly for raw materials like cobalt (from the Democratic Republic of Congo) and rare earths (primarily from China). Reducing this dependence through partnerships and trade agreements could be difficult, especially in light of geopolitical tensions and trade competition.
- **Risks from Geopolitical Instability**: Many of the countries that supply critical raw materials are politically unstable or subject to conflict. Securing long-term, reliable partnerships with these countries may be challenging and could expose the EU to supply chain disruptions.

5. Economic and Financial Constraints

- **High Costs and Investment Needs**: Achieving the CRMA's goals requires significant investments in mining, processing, recycling, and research and development. The EU would need to mobilize both public and private sector funding, which may be difficult, particularly in an environment of fiscal constraints. Private investors may be wary of investing in mining or processing projects that could face regulatory delays or local opposition.
- **Price Volatility**: Critical raw materials are subject to significant price volatility, which makes long-term investments risky. High prices can drive investment, but sudden price drops could undermine the economic feasibility of new mining or recycling projects.

6. Environmental and Social Concerns

- **Sustainability Challenges**: Mining and processing raw materials are energy-intensive and have significant environmental impacts, including pollution and habitat destruction. Even with sustainable mining practices, the ecological footprint of CRM extraction may provoke strong opposition from environmental groups, which could delay projects or increase costs.
- **Local Community Resistance**: Mining projects, even when environmentally friendly, often face opposition from local communities concerned about land use, environmental degradation, and health impacts. Securing social licenses to operate within the EU could be a challenge, particularly in densely populated regions.

7. Global Dependencies and Strategic Vulnerabilities

- **China's Dominance in Processing**: While Europe is trying to reduce its dependence on Chinese imports, China controls a large portion of the global refining and processing of critical raw materials, especially rare earth elements. Even if the EU diversifies its raw material imports, it will still be vulnerable to China's dominance in processing and refining unless it rapidly scales up its domestic capacities.

- **Lack of Alternative Suppliers**: The CRMA encourages partnerships with reliable third countries, but in reality, there are few countries outside China with the infrastructure and capacity to supply large quantities of critical raw materials. The lack of viable alternatives could make it difficult for the EU to build resilient and diversified supply chains.

Conclusion

While the EU Critical Raw Materials Act is a forward-looking initiative, its feasibility is hindered by a range of challenges. These include domestic resource limitations, regulatory hurdles, a lack of processing infrastructure, geopolitical risks, and the high costs involved in building new supply chains. To achieve its goals, the EU will need to address these weaknesses through strategic partnerships, technological innovation, and strong political coordination among its member states.

Source: @ GIS, GKZ

Social Licence to Operate: Lessons learned from the MIREU project

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SLO and where it originated from

The social licence to operate (SLO) began as an industry concept embodying the idea that the risks of not having community support were just as great as the risks of not having government support (Cooney, 2017). Local communities could delay or stop a project by protests or blockades just as government could refuse to issue a permit or licence.

Creation of the SLO term is most often attributed to James Cooney (a Canadian mining executive for Placer Dome) in 1997, when he used the phrase at a World Bank meeting to describe the importance not only of having government acceptance of a project but community acceptance too (Cooney, 2017). The focus is not on the expectation of performance but on the actual performance itself, and more specifically, on the how rather than the what industry does. Several months earlier, W. Henson Moore used the same term in a forestry magazine article to refer to the broader societal approval of an industry's practices, including the need to hold industry publicly accountable (Boutilier & Thomson, 2022). Where Cooney's definition emphasises community opinion and local stakeholders, such as municipalities, residents and neighbourhood businesses, Moore's definition emphasises societal opinion and national actors such as governments and the media. While the term soon caught on in the mining vernacular to sum up how a company should behave to win a community's support, its application to the societal level took much longer.

In the early 2000s, SLO emerged in the academic literature where it continued its theoretical evolution in parallel with its empirical evolution. SLO is a combination of theories pulled from political science, sociology and behavioural psychology (Lacey & Lamont, 2014; Parsons, Lacey, & Moffat, 2014; Poelzer & Yu, 2018; Prno & Slocombe, 2012; Suopajärvi, Umander, & Leneisja, 2019; Thomson & Joyce, 2006) woven together to explain how relationship building between a community and company can evolve ...or not (Viveros, 2016). While there has always been more emphasis on understanding the dynamics between a community and company, in the mid 2010s, Moore's idea of societal SLO emerged in the academic literature as well as in the European policy discourse, mirroring the growing importance of raw materials to the European agenda.

Although there is no agreed upon definition of the term, and there are many, one of the most widely accepted is that SLO refers to the informal and tacit presence or absence of public acceptance or support for an activity (Boutilier R. , 2014; Franks & Cohen, 2012; Gunningham, Kagan, & Thornton, 2004; Owen & Kemp, 2013). Early models (Thomson & Boutilier, 2011) were developed looking at social licence from the community perspective equating the levels of acceptance with how a community viewed a company's behaviour. Subsequent models approached acceptance from the company perspective identifying the drivers of SLO and what a company needed to focus on to achieve it (Moffat & Zhang, 2014).

How SLO is understood and applied in Europe

The SLO concept has had a slow and difficult start in Europe and continues to have problems gaining traction to this day. In fact, there still are very few examples of SLO manifesting as a trust-based relationship between community and company (Koivurova, et al., 2015). There are many reasons for this. One reason is that the public's perception of mining is largely that of a dirty dinosaur. Pictures of men working in hazardous conditions deep in a coal mine are at the forefront of this imagery. On its surface, it is a jarring juxtaposition with policy initiatives such as the Green Deal and Europe championing the United Nations Sustainable Development Goals (SDGs). Of course, there is a direct connection between mining and the energy transition, but for many people it is invisible.

A second reason has to do with Europe's industrial history and its legacy. Europe has a complicated relationship with mining. While mining has historically been a large part of the European economy, it has been in steady decline since 1988 (World Mining Data, 2024). Raw materials powered the rise of Europe's industrial centres, such as Manchester in Britain, Wallonia in Belgium and the Ruhr in Germany. Long since closed, mines and communities embracing a mining identity have vanished from these landscapes. In contrast, legacy uranium mines in eastern Europe dating from the era of the Soviet Union are yet to be properly cleaned up and bear witness to the Soviet Union's blatant disregard for both people and the environment. Ongoing lignite mining in the eastern part of Germany and the southwest of Poland consume thousands of hectares of land and leave enormous dump sites. The recent corruption scandal in Portugal in part over the concession for lithium mines only serves to reinforce the negative image of mining. And all of this is now made highly visible, constantly, because of social media. Yet, it also should be said that many communities support mining, especially if there is a need to diversify the local economy and add jobs. Even if there are protests, it does not mean everyone, or even the most relevant people, are against the mine. Anglo American's Sakatti mine in northern Finland is an example, where local people support the project but environmental NGOs oppose it because the deposit lies under a Natura 2000 area. And finally, there are many Europeans who are simply unaware or agnostic toward mining because they are not affected.

Attitudes toward mining are therefore complex, and it is no wonder the European Commission is struggling with tensions around wanting to increase domestic extraction while acknowledging the existence of a well-organised opposition. Growing geopolitical instability in conjunction with the increasing pressures from climate change have prompted the move away from importing the necessary minerals to exploiting them at home. New legislation such as the Critical Raw Materials Act[1] (CRMA) exemplifies this seeking to catalyse not only domestic mining but processing and recycling activities as well, with supply security being the short-term aim and the loftier ambition of creating a circular economy, the long-term goal.

The SLO concept arrived roughly a decade later in Europe than in Canada, where it first emerged. Although practitioners and academics alike focus on SLO as the relationship

[1] Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 Text with EEA relevance.

between a community and company, in Europe, SLO very early on was also discussed in the context of societal acceptance. Even though SLO refers to actions a company takes over and above what the law requires, meaning these are voluntary actions, it was not long before the potential role of the State and legislation became part of the SLO discourse in Europe. The strong role of the State is the third reason why SLO has had difficulty gaining traction (Lesser, Gugerell, Poelzer, Hitch, & Tost, 2020; Poelzer, 2019).

The difficulties SLO has encountered in Europe are in startling contrast to other countries where SLO has taken root and thrived, Canada being the most notable example. Not only is there a deep understanding about the development of the community-company relationship there as well as the missteps than can cause trust to evaporate, but SLO is operationalised and implemented in the form of Impact and Benefit Agreements (IBAs). Conversely, where community-company relationships in Europe exist, they appear to be of a more shallow nature. So too is the case with IBAs as there are only examples of simple compensation agreements in Europe and not yet a more robust IBA. If the differences can be summed up in one sentence, it is that the question of mining in Europe is not 'how do we mine', but whether 'we need to mine here', and if so, 'how much'. The starting point for discussion is fundamentally different.

The European Commission's role in fostering SLO and the MIREU project

With raw materials making its policy debut on the European agenda in 2008, a strategy began to form around access and supply security. As part of the Horizon 2020 (H2020) research programme in the mid 2010s, money was dedicated to the social aspect of mining, including research on social licence to operate in the European context. This did not come out of the blue, however, but was a result of the SLO concept taking root globally at the same time the United Nations adopted (in 2015) the 17 Sustainable Development Goals (SDGs). Environmental, social and economic sustainability became the leading framework for development globally, and Europe readily embraced social sustainability in the SLO concept.

In June 2018, the European Commission (EC) organized a clustering event entitled 'Social Acceptance in the European Raw Materials Sector' for 30 ongoing H2020 funded mining- and processing-related projects that had activities connected to social acceptance. In the event description was a definition of SLO defining it *as approval, consent, demands and expectations from the local community and other stakeholders in relation to specific local projects*. The focus is largely on the community-company relationship and the potential benefits that mining could bring *to everyday activities, to GDP, to manufactured goods consumption, to innovation and green technology*. The EC believed that SLO and trust-building needed to gain credibility in Europe and that it could play a role.

One of these projects with the acronym of MIREU (Mining and Metallurgy Regions of EU) was tasked with networking the administrations of Europe's mining regions and providing policy makers with SLO guidance and tools for implementation.

The Social Licence to Operate Guidelines for Europe (Figure 1) attempt to understand the divergent social dynamics around mining and chart a new path forward. Yet, the scope of challenges is made explicit in the introduction acknowledging the starting point for creating the guidelines does not assume exploration and mining can happen at any cost. Mines have both positive and negative impacts, and only if there is a fair trade-off between benefits received and impacts experienced, particularly by those who are most affected, should mining take place.

Figure 1: Cover page of the Social Licence to Operate (SLO) Guidelines for Europe (for download on: https://mireu.eu/slo

Many lessons, some of them quite challenging, were learned during the MIREU project. Over time what became clear is that the importance of a multi-stakeholder dialogue and meaningful engagement between host communities, mining companies and government are essential and difficult with so many competing concerns and expectations. The fact that the discourse around mining is still whether we should mine instead of how to mine renders largely moot the potential for furthering the SLO concept in Europe.

Is SLO incorporated in European Union and or Member State legislation?

While the term 'SLO' has not yet been enshrined in legislation either at the EU level or the Member State (MS) level, the EC has embraced the term 'public acceptance', and we see this in several new pieces of EU legislation.
Critical Raw Materials Act (2024:1252):

- Recital 9 states, *To develop the necessary expertise for the implementation of certain tasks, the Board should establish standing subgroups on financing, public acceptance, exploration..*
- Recital 19: as public acceptance of mining projects is crucial for their effective implementation, *the project promoter should also provide a plan containing measures to facilitate public acceptance. Special attention should be paid to social partners, civil society and oversight bodies.*"[2]
- Article (7)(1)(d): a strategic project should include a plan with measures to facilitate public acceptance including, where appropriate, *measures to facilitate the meaningful involvement and active participation of affected communities, the establishment of recurring communication channels with local communities, organisations, including social partners, and relevant authorities, and the implementation of awareness-raising and information campaigns and potential mitigation and compensation mechanisms.*
- Article 8: the proponent must establish and update a website with relevant information and to foster public acceptance about the strategic project.

Batteries Regulation[3] (12 July 2023): public acceptance is not explicitly mentioned but the idea is incorporated in the understanding of due diligence, a process where companies can identify, prevent, mitigate and report on how they manage the actual and potential negative impacts of the battery life cycle.

Corporate Sustainability Due Diligence Directive (May 2024): public acceptance is not explicitly mentioned but one of the aims of due diligence is public acceptance. Requirements include supply chain visibility, enhancing stakeholder engagement, designing and adopting a climate transition plan and rolling out a proactive approach to manage sustainability-related risks. A robust environmental and human rights due diligence process is emphasized.

The fact that conceptually SLO is integrated into EU and MS legislation[4], yet the term is not explicitly used, shows the power of words. Communities tend not to like the term because it comes from industry. Government tends not to like the term because it includes the word 'licence' conflating and confusing the understanding of legal licences. Whether SLO ever becomes part of the European vernacular is uncertain, but its absence emphasizes the idea that SLO is nothing if not contextual.

[2] European Commission 2024. Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials
[3] Regulation (EU) 2023/1542
[4] Please see the Finnish Mining Act of 2011 (revised in 2023) https://www.finlex.fi/en/laki/kaannokset/2011/en20110621.pdf

How SLO is seen by the EC and industry

Given there is no agreed-upon definition of SLO, its meaning and existence are in the eye of the beholder. As a concept focused on the ongoing community-company relationship and the reprioritization of company interests, two variables subject to a great deal of fluctuation, levels of SLO can differ from project to project and place to place. Generally speaking, in Europe, the desired level of SLO from the perspectives of both the EC and industry tends to be lower than in other western democracies. Where communities in places like Canada, Australia and the United States tend to want and have more decision-making power over mining projects, the relationship between community and company must be deeper and stronger. This stronger community-company bond implies a shifting of power away from the government-company relationship. As the State is a more powerful entity in social welfare democracies, such as European countries, shifting power away from government to communities is more challenging on many levels. It is not a surprise the EC embraces a relatively nominal level of SLO, even if there are references in legislation to the importance of public acceptance and the introduction of international best practice mining standards to help achieve it. As in all things, the devil is in the details. The Commission has not explicitly defined what acceptance means, how to measure it, or what to do if it simply cannot be achieved. There also are no proven tools available, the preferred fallback being company self-regulation.

Politics are part of the equation as well. In Europe, the political landscape has shifted so abruptly away from environmentalism and conservation and toward reindustrialization and security issues. Witness the CRMA and its lightning speed through the legislative process taking roughly one year when the norm for passing legislation is five. The timeframes for permitting a mine within the CRMA are also on a fast track with mining permits required to be issued within 24 months or a maximum of 27. Whether or not this can actually be achieved, however, is doubtful in the humble opinion of this author. The realization of other provisions in the CRMA are also in question, and at the end of the day, actual implementation is the responsibility of the MS and not the EC. Concerns around the CRMA nothwithstanding, the political support and economic pressures behind getting mining projects up and running provide little incentive to companies to try and gain real community support because that process often takes time, especially in areas where there are concerns and opposition. Ironically, it is in precisely these locations where more relationship-building effort is needed.

As an industry term, SLO has always been embraced by the large multi-national companies operating in Europe as meaningful community engagement tends to be built into their Corporate Social Responsibility requirements (Lindman, Ranängen, & Kauppila, 2016). These companies are used to addressing SLO because it has become an international norm. Some domestic European companies do also embrace the concept; however, unless a company believes SLO is either the right way to conduct business and/or is good for revenue generation and risk reduction, there is little incentive for companies to put additional energy and financial resources into building strong relationships. The operationalization of SLO as a means of reducing risk is not a case that has been strongly made in Europe. There is still a prevailing belief across industries of all types, not just mining, that Europe is over-regulated and best practice is synonymous with the compliance of an already burdensome regulatory system. As mentioned previously, for those companies who do embrace the concept, how it is achieved is still unknown. In other countries, companies might build hospitals and schools as part of building relationships, but in wealthy western social democracies, there is little need for a company to provide basic infrastructure. Hence, true community engagement is more complex and less forthright than other parts of the world. In Europe it is the government, ultimately, who is the gatekeeper of acceptance and this places a heavy responsibility on the EC and Member States. Unless a particular community warmly welcomes a mining project, it will be very difficult for a company alone to achieve acceptance. There must first be a perception that the legal and regulatory system ensure responsible mining and that there is accountability. Whether the CRMA and other legislation can accomplish this remains to be seen.

References

Boutilier, R. (2014). Frequently asked questions about the Social License to Operate. *Impact Assessment and Project Appraisal*, 263-272.

Boutilier, R., & Thomson, I. (2022). The Role of Historical and International Movements in Determining the Social Licence. In G. Wood, G. Mete, & J. Gorski, *The Palgrave Handbook of Social License to Operate and Energy Transitions.* Palgrave Macmillan.

Cooney, J. (2017). Reflections on the 20th anniversary of the term 'social licence'. *J. Energy Nat. Resour. Law, 35*(2), 197-200.

Franks, D. M., & Cohen, T. (2012). Social Licence in Design: Constructive technology assessment within a mineral research and development institution. *Technological Forecasting & Social Change*, 1229-1240.

Gunningham, N., Kagan, R., & Thornton, D. (2004). Social License and Environmental Protection: Why Businesses Go Beyond Compliance. *Law & Social Inquiry*, 307-341.

Koivurova, T., Buanes, A., Riabova, L., Didyk, V., Ejdemo, T., Poelzer, G., & Lesser, P. (2015). 'Social license to operate': a relevant term in Northern European mining? *Polar Geography*, 194-227.

Lacey, J., & Lamont, J. (2014). Using social contract to inform social licence to operate: an application in the Australian coal seam gas industry. *Journal of Cleaner Production*, 831-839.

Lesser, P., Gugerell, K., Poelzer, G., Hitch, M., & Tost, M. (2020). European mining and the social license to operate. *The Extractive Industries and Society*, 1-8.

Lindman, A., Ranängen, H., & Kauppila, O. (2016). Guiding corporate social responsibility practice for social license to operate: A Nordic mining perspective. *The Extractive Industries and Society*, 782-792.

Moffat, K., & Zhang, A. (2014). The paths to social licence to operate: an integrative model explaining community acceptance of mining. *Resources Policy, 39*, 61-70.

Owen, J., & Kemp, D. (2013). Social licence and mining: A critical perspective. *Resources Policy*, 29-35.

Parsons, R., Lacey, J., & Moffat, K. (2014). Maintaining legitimacy of a contested practice: How the minerals industry understands its 'social licence to operate'. *Resources Policy*, 83-90.

Poelzer, G. (2019). A view from the top: State perspectives on legitimacy and the mine development process. *Environmental Science and Policy*, 3-24.

Poelzer, G., & Yu, S. (2018). All trust is local: Sustainable development, trust in government and legitimacy in northern mining projects. *Resources Policy*, 3-24.

Prno, J., & Slocombe, S. (2012). Exploring the origins of 'social license to operate' in the mining sector: perspectives from governance and sustainability theories. *Resources Policy*, 346-357.

Reichl, C. & Schatz, M. (2024). World Mining Data 2024, Federal Ministry of Finance, Republic of Austria. Volume 39 Minerals Production Vienna

Suopajärvi, L., Umander, K., & Leneisja, J. (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*, 1-7.

Thomson, I., & Boutilier, R. (2011). The social license to operate. *SME Mining Engineering Handbook*, 1779-1796.

Thomson, I., & Joyce, S. (2006). Changing Mineral Exploration Industry Approaches to Sustainability. *Society of Economic Geologists*, 1-21.

Viveros, H. (2016). Managerial perceptions of stakeholder salience in mining. *The Extractive Industries and Society, 3*, 987-996.

Young Careers

Source: GKZ, Stock

Insights of Gen Z about sourcing Europe

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As part of a so-called Focus Group Meeting, the GREENPEG project took a good 20 students on an excursion through northwest Spain in the fall of 2023 to sites of industrial generation of renewable energies and the extraction of the necessary raw materials. The students came from eight European countries. The target group were those with courses related to the twin transition (digital and energy) in the field of social sciences and engineering, which usually teach little about the raw materials industry for said transformation processes nor provide insights into the practical world of raw materials extraction and renewable energy generation.

Figure 1: How many aggregates and cement were needed for the concrete to build the dam? Group photo at the Aldeadávila Dam in NW Spain.

The aim was also to show how high the CO_2 footprint of the construction of renewable energy plants is with regard to the raw materials used. Be it the provision of concrete for the construction of an ocean wave power plant or a hydroelectric power plant dam, the foundation of wind turbines or the use of large-scale storage systems for electricity generated by solar parks with the battery metals they contain. As part of this week-long study trip, a round table was held at the University of Salamanca with representatives from the local mining industry, licensing authorities, the Geological Survey, environmental associations and affected communities. Following this round table, the students were requested to answer a questionnaire with the aim of asking the young people about their attitudes to issues such as securing Europe's raw materials and energy, our responsibility for the world we live in and political approaches to solving the pressing tasks of social and economic challenges in the context of the EU sourcing policy.

Although the participants do not represent the entirety of Gen Z, they correspond to the age spectrum and, above all, represent an important link between the humanities and

engineering and the natural sciences. They have clear viewpoints on several key and relevant issues. As a first, they are Europeans in their beliefs and their mentalities.
This implies that they see common European interests and, hence, "responsibilities for Europe", by way of example in providing industry and consumers with required natural resources for Europe's needs. An example at hand is the European Green Deal with the Energy Transition. This is seen as a big task for Europe and its current and next generations.

When it comes to the required natural resources, generally speaking, in their views, it is not fair for Europe to procure all of them from outside through imports and not spend time and efforts on developing and maintaining a natural resource base within Europe. Students stated that traditional mining countries in Africa and Latin America should continue their mining operations but with enhanced ethical and environmental standards. In terms of domestic mining. Europe has a potential – be it big or small – to reduce the burden it places on resource-rich countries around the world and, at the same time, its dependency on such countries. This is considered as a win-win strategy. Since Europe also has the potential for the development of a circular economy, its reliance on recycling can boost this win-win situation. Finally, it is felt that Europe disposes of manifold options to reduce consumption as a measure of resources conservation.

This ample and comprehensive view of Europe's resource base is strongly present in the minds and convictions of the participants. One student wrote:

A strong industry that serves a sustainable society, yes. A strong industry, to serve its own standing, no.

And, in the same context:

A strong industry could be linked with the following UN Sustainable Development Goals:

> *Goal 1- No Poverty – by providing job opportunities*
> *Goal 9- Infrastucture, Innovation and Industry- In the names, but it will improve over all living standards*
> *Goal 10 Reduced Inequalities: Proving job opportunities to minorities and previous under-represented peoples*
> *Goal 12- Responsible Consumer and Production- by regulating businesses to consider a circular economy*

Students also argue that, however, prior to opening up a new mine, the focus should be on reduced consumption patterns. But they also acknowledge that mining is an integral part of our economy. Here are some statements:

"It is right to expand domestic mining, to be independent and reduce climate impact by avoiding long transport routes. But mining should not be expanded just to fuel."

Another student observed:

"in Germany more than every 2nd person statistically has a car, replacing them all with EVs is just too much, we need to lower the amount of cars and change our mobility behavior by improving the train system for example."

A diversified economy, of which mining can be a part.

Students know about the bad image of mining:

Dissemination tools must be used so that mining reaches society as something good and necessary

Students are aware that this change of focus with more and new mining in Europe implies that all interests are balanced out, because Europe is a democratic continent. Cultural differences among Europe's regions and nations are similarly important. In this process, some state that no region can be left behind and that not all regions and nations are at same levels for specific key tasks, such as moving towards energy from renewable sources, tackling climate change, developing innovative mobility concepts, establishing a circular economy and, not in the least, raising awareness for all these tasks with their citizens.

Students state that "Europe" cannot march ahead with one single speed and with one and only one strategy and toolbox. Instead, a manifold of approaches is required, even if the goals, such a decarbonization of Europe's economy in the coming years is to be shared by all.

When it comes to the delivery of personal contributions, perceptions of students are very mixed. Some see themselves as future scholars with opportunities to do research work on all these issues and to communicate their results. Their role is to bring out "facts and figures" and reliable forecasts on the outcomes of efforts towards the Green Deal in order to inform citizens and help them with their awareness for changes and their potential benefits. In this way, they see themselves as ambassadors of Europe's new Green Deal. Here are some statements by students.

We cannot always expect the world to be our resource supplier. We also need to take advantage of our own deposits. Me as an individual cannot do much about this but I can vote politicians, who will hopefully take care of good policies.

I have contributed with dissemination through research, lectures, courses, and good communication with people around me, helping to disseminate scientific facts, causing critical thinking in the Portuguese people.

I see it as the task of politics to create measures that address this issue. But it is also the responsibility of the society to make politicians more aware of this issue.

Europe's Green Deal

With the Green Deal and its components, such as Energy Transition, E-Mobility and Decarbonization, participants believe that mining in Europe should be given a new chance for reasons already stated above and local and regional development, especially in areas which fall behind. For a successful expansion and revival, they see a necessity to bring all interested stakeholders on board in a well-formulated agreement. Here are some students' opinions:

The Green Deal is not just a project for investing in mining exploration in critical raw materials, but also for the recovery of biodiversity

The energy transition seeks to benefit human beings, but it cannot be bypassing the rest of the communities that make up our ecosystem. It would not make sense, since seeking to preserve the planet (in the sense of climate change mitigation) cannot imply destroying our ecosystems and their ecology.

This ("the energy transition") requires a prior recovery and impact plan and subsequent environmental monitoring … of how certain organisms undergo changes depending on the conditions of the environment.

Awareness of renewable energy development comprises an evaluation of land use and impacts on bio-diversity. In this respect, students expressed concerns and optimism at the same time. Here are a few comments.

Wind and solar can harmonize very good with agriculture. Bioenergy is more problematic.

There are examples of sites where both renewable generation and agricultural processes coexist, one does not necessarily have to displace the other. These should be assessed on a case by case basis … There is no equilibrium. And the knowledge about aeolic parks, for example, has underestimated ecological consequences in killing animals

Green Deal and nuclear power

In this context, the issue of a renewed interest in nuclear power as an energy generation technology with limited impacts on climate change received a very mixed assessment. There are positive views, critical views and outright rejections.

In order to accelerate the transition towards a carbon free future, there needs to be an energy mix comprised of different sources, and nuclear can provide that.

If nuclear power is an option to expand an existing plant or maximize its capacity, then … this should be considered before using a gas or coal fired plant

Nuclear energy might be considered green but the mining (on Uranium) currently doesn't hold that status, it is important that regulations are in place to minimize its impact on the natural environment and that thought is put into the cost of processing and transporting in terms of the CO_2 footprint of nuclear power

All mining projects have to comply with the existing regulations, including those with radioactive elements. Therefore, toxic waste will have to be properly treated in a licensed plant; safety is a crucial issue.

As the waste handling of uranium (post mining and post energy generation) is not at all existing, this cannot comply with an honest approach for a sustainable transformation, the Green Deal claims to be.

The scenario in question is not realistic. There are but a few places around the world where it actually is possible to replace nuclear with coal and gas on a scale that would matter. In most places the necessary plants are not in place or serve different use-cases and planning and construction would simply not be quick enough.

From an economic point of view nuclear power is too expensive and takes too long to be built, so it won't necessarily experience a revival.

It (the revival of uranium mining) has to be guaranteed for a certain period of time in order to be able to realize such projects at all.

Committed increase in renewables is not only cheaper, but also more reliant in the long term. With the changes we face today, the supply with neither nuclear or fossil fuel can no longer be ensured for specific locations that would be locked on for the next 50+ years.

Already today, a close to 100% RES-based energy system is possible.

Europe's leadership in the world

Students agree that (i) Europe (still) has a leadership role of green industry in the world and (ii) Europe should maintain this role and (iii) there are good reasons for this. They even favour a strong commitment to keeping Europe's leadership role, since:

- there is no need to give it up
- Europe has a moral obligation
- Europe can assist other countries with its technology leap
- Europe can demonstrate the economic benefits of climate-neutral technologies to other countries
- Europe can benefit from the implementation of such technologies by such countries

As one student wrote:
At the moment, we have the privilege of not giving up our global market leadership and continuing to insist that we can only justify renewable energy sources if they are profitable. When the tipping point is reached and it really is a question of mitigating the climate catastrophe and survival, no-one will ask about it any more...

Summary

As stated above, mining In Europe makes EU member states less dependent on such mining countries and allows them to create circular economies. In addition, a new or renewed resource base in Europe supports not only the Green Deal, but also the space and aeronautics and defense industries and, not in the least, digital technologies development a and Europe 4.0 as grand challenges. Students believe that Europe can benefit from a new economic policy of partial self- reliance on global natural resource markets for its demand. On the one hand, this provides options to increase Europe's self-supply of natural resources as a benefit to entire downstream value creating chains. On the other hand, students agree that the mostly locally generated negative impacts of mining operations on eco-systems, infrastructure, water resources and land-use should be mitigated and that mining regions are entitled to a substantial value added of the entire product chain. In order to achieve this contribution of mining in Europe to its resource base and the Green Deal, students name the following tools.

- identification of needs and limitations of each stakeholder
- consciousness raising for awareness of the importance of raw materials
- information of the implications of mining for local communities (pros and cons, disadvantages and benefits)
- communication instruments for transparency of processes
- balancing mining and nature conservation, for instance through the creation of equivalent substitute nature protection areas
- design of mine site rehabilitation plans
- support and incentives for the mining industry resulting in sustainable investment

Final quote:
I don't see any need to weigh one "economic activity" against another. It is not about this or that branch of industry in specific. We should rather focus on what is the benefit or impact for society!

Insights from the GREENPEG Summer School – meeting the young careers

Kate Smith[1], Meng-Chun Lee[2]

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Background

The idea of organising a GREENPEG Summer School originated from the concern that there would be little use for even the most innovative exploration technology without a younger generation of geologists, geophysicist or mineralogists who can make use of it. A summer school would be ideal to educate the younger generation about the GREENPEG technologies and methodologies and introduce them into a professional career in raw materials sciences in the hope of helping Europe to secure skilled labour for the future.
Considering the aforementioned expectations, the two-week long GREENPEG Summer School at Tysfjord, Norway, one of the GREENPEG demonstration sites, focused on a theoretical and practical introduction into advanced non-destructive exploration techniques. It aimed at a dual education with a strong practical insight into the pegmatite exploration as one of the most popular exploration targets in the upcoming years in Europe. The target group is Master and PhD students studying in geosciences for instance, geochemistry, geophysics, ore & economic geology as well as felsic magmatic systems.
This offer was met with a great deal of interest. By the application deadline, we received in total 64 applications from students studying in 12 European countries with diverse nationalities. Some of them expressed their plan to have a career in the exploration and mining industry while the others would like to continue pursue an academic career. There are a few who also indicated their wish to bring the latest knowledge back to their home countries. Most of them see this as a great opportunity to network with professionals and peers working in the same field. In addition, the activeness of a number of students in relevant short courses, EU funded projects, European Exploration Targeting Boot Camps, etc. is a pleasant surprise. We were glad to see how well the aspirations of the students matched with different aspects of the GREENPEG project: securing future skilled labour for the industry; further research and innovations; promoting knowledge and technologies "Made in Europe"; and sharing the European Spirit.

Figure 1: Applications came from students studying in 12 European countries

Regrettably, we could not accept them all. In the end, based on a pre-determined criteria, 12 students from 9 countries were selected to participate in the GREENPEG Summer School from 19th to 30th July 2023. During the 14 days, the students had indoor lectures in the mornings and practical sessions in the field in the afternoon covering topics including geochemical mapping of pegmatite fields, geophysical exploration methods, drone-borne hyper-spectral data acquisition, remote sensing exploration, satellite data interpretation, life cycle assessment for exploration and mining, critical raw materials and circular economy. Besides the lectures and practical sessions, an Open Day with the local community was organised and took place at the Arran Sami Center.

Here we would like to share feedback from the participating students, their insights into the highlights of the summer school and their visions for the future of mineral exploration in Europe. We are delighted that the response of the students to the summer school was extremely positive and more than fulfilled the student's expectations. The practical sessions clearly left a strong impression on the students as they got to personally experience the beauty of the site and application of various exploration techniques. According to their feedback, we could tell that the students were aware about the risks of overdependent on the global raw materials supply. They thought pegmatites provide an opportunity to reduce such risks especially considering its occurence is relatively common in Europe. On the other hand, they expressed their concerns regarding the challenge in sourcing of raw materials in Europe. For instance, the need of rebuilding trust and responsible practices were emphasised. One of them also mentioned the importance of economic feasibility of a project. To sum up, the GREENPEG Summer School opens their minds to different possibilities for their future careers, as well as provides them with different perspectives on how their professions could contribute to society.

Voices

What did you hope the summer school would offer you, and has this been fulfilled?

"I hoped that the summer school would equip me with a tool kit specific to pegmatite exploration and add to my existing theoretical knowledge acquired as part of my PhD. Although I have experience of LCT pegmatites in Europe, the opportunity to be introduced to the rarer NYF- type pegmatite has taught me more about the different resources that can be sourced from pegmatites. It was also a fantastic opportunity to connect with other geologists from across Europe interested in this field of study. The summer school has been absolutely fantastic and surpassed all expectation. I got a great deal from the course and I'm truly grateful for the opportunity to attend, thank you."

"All my expectations have been more than fulfilled! Theory lessons in the morning and field work in the afternoon were an excellent combination in order to understand the scientific background of the methods and also how to properly use them in the field."

Are there particular bits of the summer school that have really resonated with you, or particular lessons that you will take away with you?

“From a practical perspective the GREENPEG exploration workflow was very interesting, particularly the application of non-intrusive geophysical and low impact sampling techniques during early-stage exploration.”

“During all the lessons and practical things, the importance of pegmatites for the future of European mining was explained to us in detail. This huge importance is definitely one lesson I will take away with me. …Another important point is a functioning cooperation between geologists, geophysicists, mineralogists in order to find and characterize future mining areas.”

“The message which resonated with me most is the need to tailor the techniques utilised to the specific pegmatite deposit type, as the effectiveness of each technique varies even between similar pegmatites based on both geological and environmental factors.”

“I will especially remember the geophysical methods. Before, I did not have the opportunity to work with the instruments in the field or to work with geophysical methods. Therefore, it was especially great to get an impression in this regard.”

“the visit to the pegmatite with Amazonite: an incredible experience that makes you realize the beauty and diversity of geology”

“The 3 most important things I will remember are: Keep going [with] what you are passionate about, irrespective of your particular field of study; be aware [of] who you might meet and be kind to each other; enjoy the fascinating things that you see for the first time!”

Figure 2: Introduction into the geological setting of the Jennyhaugen Pegmatite, Tysfjord, Norway

What do you think might be the key opportunities and challenges of securing a future raw material supply for Europe?

"In terms of opportunity, Europe undoubtedly possesses world class pegmatite fields encompassing both LCT and NYF-pegmatites which host a plethora of critical elements essential for the green revolution. However, as well as offering the opportunity to maintain control over our future raw material supply, it also offers us an opportunity, as Europe, to lead the way in responsible and ethical mineral exploration and extraction."

"The regain of trust in the business is I think the key challenge in supplying raw materials (from Europe) to Europe."

"Finding suitable locations for mining operations while minimizing the impact on local communities and ecosystems is a delicate balancing act. … Cooperation and coordination among European nations are crucial to overcome these hurdles and establish a framework that promotes responsible mining practices."

"The importance of a local raw material supply is … of political concern, as potential future trade embargos could seriously threaten the supply of critical raw materials to the European community. A local supply could mitigate some of these issues and prevent large-scale manufacturing disruption."

"Work by projects such as GREENPEG is helping to bring smaller-scale metal deposits, of which Europe contains many, into economic viability by reducing the costs associated with exploration."

"If raw materials could be explored and mined specifically in Europe… mining for raw material supply could be designed according to European environmental standards and working conditions"

What, at the moment, do you think you might plan/hope to do in a future professional career?

"What fascinates me most is the exploration, mining and processing of lithium and rare earth elements, because these deposits are so diverse and unique from a geological point of view."

"After my PhD, I hope to work directly in mineral exploration or another mining-related field, such as mining and metals consultancy or in a financial analyst role."

"Two years ago, I would answer that an academic career would be a very exciting path, but there are so many good opportunities in the industry now. The market for industrial minerals focused on green energy is one of them, so my plan is to get as much professional experience as I can in the next few years" “what I like about the geology of mineral deposits is, that on the one hand you can explore geological settings worldwide for raw materials and on the other hand, you can contribute to society by meeting the demand for resources such as ores.”

Our experience with the students defied the stereotypical view of the older generations towards Generation Z (i.e., the group of people born between the late 1990s and the early 2010s). In contrast to lack of motivation and goals, the students were proactive and passionate about the subjects taught. Furthermore, they showed that they found great enjoyment in traveling for exploring new deposits.
Many of the 64 applications appeared to be young Europeans who utilize the opportunities of their time, such as participating in the EU ERASMUS programme or internships on their own initiative. Some students were strongly socially and politically engaged. Nevertheless, most of them when asked what prompted them to study their subjects, explained that they were primarily interested in understanding the Earth system. Choosing subjects based on career relevance is less of a priority. Overall, more students lean towards pursuing an academic career rather than going into industry.
The GREENPEG team is very happy to have hosted these talented students and have successfully educated, up-skilled and motivated the next generation of exploration geologists.


NORDSALTEN AVIS Fredag 30. juni 2023 5

Studenter fra hele Europa på Drag

Studentene på Nyhaugen på Drag. Foto: Encarnacion Roda-Robles

På grunn av økende etterspørsel etter grønn energi og spesifikke mineraler, var 12 studenter i Hamarøy for å lære å lete etter litium og pegmatitter.

Tekst: Heidi Vinnes

Prosjektet GREENPEG er finan- ...

... ge Dublin, NTNU og Universitetet i Oslo.

– Studentene er fra syv forskjel- ...

... 50 x 40 kilometer i Hamarøy kommune. Jorddekke og vegetasjon her er en interessant utfordring i ...

Disse studentene er på sommerskole i Hamarøy. Her skal de lære å lete etter høyt etterspurte mineraler som kan brukes til å utvikle grønn energi. Foto: Alex Müller

Figure 3: Even a Norwegian newspaper reported from the GREENPEG Summer School

GREENPEG in my country – scientific and social experiences in the Zambézia Pegmatite province, Mozambique - An approach to an African country where real societal challenges exist

Violeta Lavínia Bunzula, Geokompetenzzentrum Freiberg e.V., Freiberg, Germany

Mozambique is a southeast African country bordered by Tanzania in the north, Malawi and Zambia in the northwest, Zimbabwe in the west, Eswatini and South Africa in the southwest and the Indian Ocean in the east. It is characterized by a mixture of peoples, cultures, and religions, and a vast and varied landscape, home to a rich and diverse array of species, ranging from the famous big five (elephant, rhinoceros, lion, buffalo, leopard) to reptiles and amphibians. Mozambique is also geologically diverse. It´s geological structure is characterised by southern, central, and northern zones. The central zone contains the oldest rocks, Archean, as well as Proterozoic and Phanerozoic units. The north zone primarily consists of Proterozoic units, and the southern zone comprises Phanerozoic units. The geological resources include high-quality iron ore, tantalite, gold, bauxite, graphite, marble, bentonite, limestone, sea salt extracted from coastal areas, and heavy mineral sands. Mozambique's other mineral resources include manganese, graphite, coal, fluorite, platinum, nickel, uranium, asbestos, and diamonds.

My name is Violeta Lavínia Bunzula, and I have a master´s degree in Economic Geology from the TU Bergakademie Freiberg, Germany. I'm a young Mozambican woman who grew up on the shores of the Indian Ocean in a small town called Xai-xai, which offered us the best seafood and taught me to pay attention and look for the best seashells to take home on Sundays. It was on those shores of the Indian Ocean that I began my preparation to become a geologist to look carefully and search for the best gifts our planet could give.

Figure 1: The captivating late sunset view of Xai-xai Beach, Mozambique.

I was raised by very strong women who taught me from an early age that education and hard work are the only ways to succeed and change the reality we live in. These women always allowed me to dream and to believe that borders were only doors that I could open if I put my mind to it. And that Europe was a continent far away, but that if I put my mind to it, I would get there and learn science the way Europeans do.

Study in Germany

Hence, I dedicated myself to my studies, aiming to get good grades and be admitted to a scholarship program. The effort was worth it, and the Mozambican Ministry of Mineral Resources and Energy offered me a scholarship to study geology at the TU Bergakademie Freiberg (TUBAF) in Germany. Germany gave me a cold welcome. I wasn't used to such low temperatures, and I came from a country where the sea water was warm. Without the sea, without the fresh gifts of the sea, and without my family, I had to adapt to a country that was completely different from my own. I learned to be a university student, but most of all, I learned to be a black university student. During the 17 years I lived in Mozambique, I never felt black, nor did I have to feel uncomfortable because of my skin colour and that you had the feeling of not being accepted right away. But the decision was made, and I had to learn to put those feelings apart because I was fulfilling my dream of being able to learn as the Europeans do and trying to understand the way they feel and they are.
So, I had the chance to knock on a door that introduced me to a welcoming environment that accepted me the way I am. In 2019, I was hired as an intern at the local consultant company BEAK Consultant to help develop a database for the Ministry of Mineral Resources and Energy of Mozambique (MIREME). During my three years at BEAK, I learned a lot. I gained confidence in working with ArcGis, improving my English, learning how to work as part of a wonderful and supportive team, and, most importantly, learning how to learn in a completely different environment than I was used to. As a result of all this learning, I completed my Bachelor's thesis, "Pegmatite of Nampula Block in NE Mozambique: An Inventory of Existing Knowledge and Predictive Mapping." As I like to challenge myself and never become complacent, I decided to go further. Thanks to Erasmus+, I spent the first year of my Master's at the University of Coimbra in Portugal, where I got to know other areas of geology and other ways of life.

" Opportunities multiply as they are seized." - Sun Tzu

Opportunities are all around us, we just need to broaden our vision to realise them in the most common places and occasions. University is a gateway to opportunity, and it is here that we establish ourselves as adults, gain responsibility, make individual choices, and gain and spend energy. At Freiberg, I had the opportunity to get to know Geokompetenzzentrum Freiberg e.V. (GKZ), which was a turning point in my career, as it made a positive contribution to its growth. With no knowledge of rock blasting or even a passing interest in the subject, I seized the opportunity to take part in the Basic course "General Blasting Work" in combination with the special course "Industrial Blasting" as part of the German Development Cooperation Project BLP*[1] Saxony-Mozambique initiated and coordinated by GKZ. The main aim of this project was to capacitate IGREME inspectors in rock blasting and ILO C176 as part of a long-lasting collaboration in legal and administrative capacity building between Germany/Saxony and Mozambique which started 8 years ago.

*[1] Bund-Länder-Program (German Government and Federal States Program): A joint measure of development aid and collaboration under the Federal Ministry of Economic Cooperation and Development).

The program had the aim to support the Mozambican Ministry of Mines and Energy (MIREME) in the area of good governance in the extractive sector and in the creation of legal and institutional framework conditions. Focusing on building local capacities and the expansion of cooperation with experienced German partners from Saxony like members of Geokompetenzzentrum Freiberg e.V. within the overall programme implementation of BLP projects by Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

Figure 2: During the Bund-Länder-Programm (BLP) Sachsen-Mozambique: ILO C176 workshop in Maputo with IGREME inspectors in 2022.

Although Mozambique has a long mining tradition, the industrialization and upscaling of mining processes as well as the increasing mining carried out by foreign companies require the optimization of mining safety as well as to update the mining law and to make sure that it is fully enforced.

Mozambique has a long tradition with Saxony. In the socialist era, Saxon Geologists participated in joint raw materials exploration and mine development in coal and metal mining in Mozambique. Further, young Mozambicans were sent to Freiberg to study at TUBAF and work in the well-known mines of Saxony. After finishing their studies, the geologists and mining engineers returned to their home country with good knowledge also in German. Quite a few of those alumni went on to take up management positions in the mining industry and government. This is where today´s Saxon-Mozambican partnership comes in, and more young Mozambicans have come to Saxony since 2014 to continue this legacy. During the BLP project, in a conversation with GKZ, I learnt about the GREENPEG project, which, in addition to its studies on the pegmatites located in European countries, had plans to verify a toolset in countries with a tropical climate and thus tropical soil cover. In 2022 a delegation from MIREME was invited by the Saxon State Government and attended also the general assembly of the GREENPEG project in Dresden at that time, with the objective of establishing a partnership with GREENPEG. I had the great privilege of being included in this delegation, where I was afforded an opportunity to deliver a presentation about the pegmatite deposits in Mozambique where GREENPEG's toolset could be test and potentially applied.

Figure 3: GREENPEG General Assembly in Dresden (2022) at the Fortress Königstein. The Mozambican delegation from the Ministry of Minerals & Energy Resources represented by General Inspector and former TUBAF student Dipl. Ing. Obete Matine, MIREME Geologist Vladimiro João Manhiça, and TUBAF former student M.Sc. Violeta Bunzula - Inspectorate (IGREME), Dr Wolfgang Reimer from Geokompetenzzentrum Freiberg e.V. (GKZ). Phot: GKZ

In the internship with BEAK Consultants, I gained knowledge in creating a prognostic map of pegmatite deposits in the Alto Ligonha pegmatite district. This experience and due to the integration of my person in the ongoing work with the BLP Project allowed me to join GKZ and to be sent to Mozambique for GREENPEG fieldwork. More than this, it provided me with the opportunity for my master's thesis on "Lithium pegmatites of the Alto Ligonha Field Mozambique: Economic assessment by applying mineral chemistry," as part of the GREENPEG project and to work with Prof. Axel Müller from the University of Oslo (UiO), coordinator of the GREENPEG project. This, in turn, allowed me to travel to Oslo and Potsdam to work with EPMA, SEM and LA-ICP-MS instruments in order to analyse the samples collected in August 2023 during the fieldwork conducted in the Alto Ligonha pegmatite field in Mozambique. Once again, I had the opportunity to learn and work in a multidisciplinary team.

Figure 4: Fieldwork team consists of Geologists from INAMI (Azarias Macuacua, Gonçalves Manhique, Chibaele, Silvio Ribeiro), Violeta Bunzula and Professor from UiO (Prof. Axel Müller).

"But those who suffer, God delivers in their suffering; he speaks to them in their affliction." - Job 36:15

Throughout the hard times and challenges I faced during my integration into Freiberg, I met some incredible people who opened many life-changing doors for me and, with mutual respect, helped me along my path as a university student in Germany. I'm very grateful to Ms Hilke Domsch and Dr Wolfgang Reimer (GKZ) for the opportunity to participate in the BLP Sachsen-Mozambique project and for introducing me into the GREENPEG project. In less than a year of doing my master's thesis, I had the opportunity to learn a lot from Prof. Axel Müller, to whom I will be immensely grateful for his support not only for being one of the supervisors of my master thesis but for being a great mentor.

Pegmatites in Mozambique

Pegmatites in Mozambique are found in the central part of the country, including Sofala, Manica, and Tete provinces. The most significant deposits however, are located in the northern region (Zambézia, Nampula, Cabo Delgado, and Niassa provinces), primarily in Zambézia and Nampula provinces.

The Alto Ligonha pegmatite field is situated northeast of the Zambézia province and has a humid tropical climate with distinct wet and dry seasons. The wet season typically occurs from November to April and is characterized by higher rainfall, while the dry season extends from May to October. The average temperatures are between 24 and 26° C, and the precipitation amounts are between 800 to 1.000 mm/year. This leads to intensive tropical weathering and depleted soils.

The Alto Ligonha is an important rare-metal pegmatite field of notable economic significance within the country. It is renowned for its abundance of industrial minerals, rare metals (REE, Be, Nb-Ta, U-Th), and gemstones. These include tourmaline, beryl, columbite-tantalite, spodumene, Li-micas, and kaolinite. Therefore, in the context of the energy transition, the considerable rise in global demand for lithium for the manufacturing of lithium-ion batteries has resulted in the regaining of the economic importance of pegmatites of Alto Ligonha, especially for the extraction of lithium micas and spodumene.

Figure 5: Spodumene from Napepesso artisanal mine in Alto Ligonha pegmatite field prepared to be sold.

Due to the socio-economic challenges in Mozambique, lithium mining activities within the Alto Ligonha pegmatite district are predominantly undertaken by artisanal miners operating in the form of associations and cooperatives. Despite being officially sanctioned by the government, these miners employ outdated methods that lack adequate safety measures and environmental sustainability, as well as, in some cases, child labour.

Figure 6: Miners from the Nacomile Cooperative in Napepesso artisanal mine during lepidolite and spodumene extraction work.

Mining companies from Mozambique, China, France, and Italy are present in Alto Ligonha. Their main focus is the exploitation of columbite-tantalite, beryl, tourmaline, and, in some cases, Rb-rich micas. Lithium minerals such as spodumene are not considered primary products because they are only located in the central zone of the pegmatites and have a Li_2O content between 2.3 and 5 wt.%, which is considered low.

Lithium minerals from the pegmatites of Alto Ligonha have been commercialised for the Chinese market. Mozambique has long-standing and close trade ties with the Republic of China, and consequently, it is easy to export and import products.

The exploitation of pegmatites in Alto Ligonha faces several challenges, such as precarious infrastructure, including poorly maintained roads, long distances to travel to nearby villages and/or the N1 national road, unskilled labour and limitations in the availability of geological information, as well as climatic challenges (rainy season, high summer temperatures). Tropical weathering has altered most of the pegmatite minerals, which, on the one hand, allows the extraction of ores without heavy machinery and/or explosives. On the other hand, it lowers the Li content of the Li-bearing minerals.

Figure 7: Construction of the processing plant at the Naipa mine owned by French and Mozambican partners.

A future as a geologist in Mozambique

Mozambique is a developing country, so the number of skilled labourers is growing, laws are being improved to match those in force at the border, more access roads are being opened, and the government has created new departments to meet the needs of the mining sector. My master's thesis at the TU Bergakademie Freiberg, supported by GREENPEG, UiO, IGREME, GFZ Potsdam, and GKZ, will help the mining sector, especially in the exploration and marketing of lithium minerals. The government will have more data to better control the products being marketed, prospectors will know what they are selling, and future investors will have a better geological knowledge of the area, thus saving time and money.

I have successfully completed my studies in Germany and Norway and I am now in a position to contribute to the development of my country, drawing on the knowledge and expertise gained during my time in Europe. I was fortunate to have the opportunity to collaborate with the MIREME on my two theses, but I recognise that as a young Mozambican, I have a responsibility to play an active role in shaping the future of my country also in a more social manner.

My aims is to work as a geologist in close collaboration with small-scale miners, sharing the knowledge I have acquired over eight years in Europe and assisting them in identifying solutions to the challenges inherent to small-scale mining. These solutions aim to enhance the environmental sustainability, security, and profitability of their operations. In addition to helping in the mining industry, I plan to create a project to help orphans (especially girls) and/or those with financial problems to acquire knowledge and to complete their studies. The objective is to prevent the number of premature marriages and pregnancies from increasing, thus contributing to an increase in the number of skilled workers.

Figure 8: This photograph commemorates the success of my master's thesis defence, held in front of the monument to the city's founder, Margrave Otto the Rich, and the four lions in armour.

My story – from Damascus to Freiberg

Sipan Hasan, Berlin, Germany

Damascus, Syrian civil war in 2015

The summer of 2015 had just begun and the high heat in Damascus started. What made that heat worse were the mortars, whose sounds we used to sleep and wake up to. When I walk the streets, I see the destruction that became a familiar look in Damascus. It used to be the most beautiful city in my eyes. I look at the peoples´ faces and I see shadows walking around me. It became rare to see a real smile from the heart, everyone is walking around but they are still stuck in the past. Every time I talk to someone, they start by saying “remember how we were”. I started seeing the destruction of people’s souls. The elderly people are sad about their city and what it has become. The children did not get to see how the city was; they did not get to feel the safety that we used to have. Young men like me are trying to follow their dreams, still hoping that Damascus will go back to how it was or else trying to leave the country.

Under those conditions, the decision to leave was difficult but necessary. It was the best decision that anyone could take, but just the idea of leaving everything behind was terrifying - leaving my home, university, family and friends… everything… and deciding to leave. But following my sisters´ messages encouraging me to travel to Germany where she lived, the decision was made.

In my last days in Syria, I was really aware that I could not tell anyone that I am planning to leave the country because of the compulsory military service. I even could not say goodbye to my family because they used to live in another city and I was in Damascus, and because of the war, going there was extremely dangerous.

Boat people

My first destination after leaving Syria was Turkey, where I stayed for about twenty days in one of my relatives´ apartment, and in these days, I met another four guys and we became friends and decided to stick together for the whole journey. So, we spent these days trying to collect as much information as possible about the best city to start from, and the costs, as well as trying to find a smuggler to help us to reach Greece. Finally, we knew that we should start from Izmir and that it will cost us about 1200 dollars each, which was a lot for me and I had to ask my brother who finally borrowed the cash for me. After we found a smuggler, and after giving him the money and some failed attempts, which ended up by us getting him arrested, came the promised day. The day which we will get on the death boats looking for a better, safer life. This was the goal that everyone shared at that moment.

On the beach there were a lot of people. Most of them were young men and we were trying our best to not make any loud noises and risking getting caught by the police, who were all around the place watching out for us. Then it was the time to get on the boats going to Greece. Everyone hesitated for a moment, but then we were able to pull it together and to get on the boat. However, in the last minute, there was a family who decided to not get on the boat because they were so afraid. We started sailing and luckily the sea was calm. Even though it took us six hours to reach Greece, it was six hours of absolute silence, a silence which was only broken by the guidance of me and other two guys to help the "captain" keeping the right destination.

It wasn't easy to ignore the looks of hope and fear at the same time from those around me. Just to reach the land safely was like being reborn for all of us. After reaching the shores safely and seeing the people hugging each other with a smile on their faces, the fear started to vanish, and I spent that night sleeping on the harbour floor. Even though I was sleeping on a concrete floor, the sleep that I got that night was deep and full of comfort because of arriving safely.

The next day we completed the route to Athens and then we started moving from one country to another with small breaks to eat something or to rest for a while. Some distances we would travel by bus, which was our sleep time, otherwise we would stay awake. We continued like this for about four days, until we arrived in the Hungarian capital of Budapest. I will never forget the people who helped us on the way with water, food, and warm clothes.

Whoever comes in is in

Now came the most difficult part, as it became clear that Germany was the destination for quite a few people. We knew from the media reports about the real flood of people who wanted to come in. And we knew about the welcoming culture of the Germans, but also about their fears. Would the border remain open? From Budapest we set off in a closed car through Austria and arrived to Germany in southern Bayern. As soon as we entered the German border, the driver ordered us to disembark immediately and that his mission was over here, we arrived at midnight and there was no one on the streets and we were lost not knowing where we were or what to do.

For me, I wanted to get to Saxony where my sister lives, and here I decided to go to the nearest train station. But all of a sudden, one of the women who was with us in the closed car, came to me and started saying that her little boy had an extremely high fever and asked for help. I was the only one who could speak English, and I knew then that if I called an ambulance, the police would come and that means I wouldn't be able to make it to my sister's. But before I called, I noticed an ambulance car returning from somewhere so I started waving for them to stop. They stopped and helped the baby and they even called the cops because they had to. After the police came, they took us all to the nearest refugee center and there my new life had started in Germany.

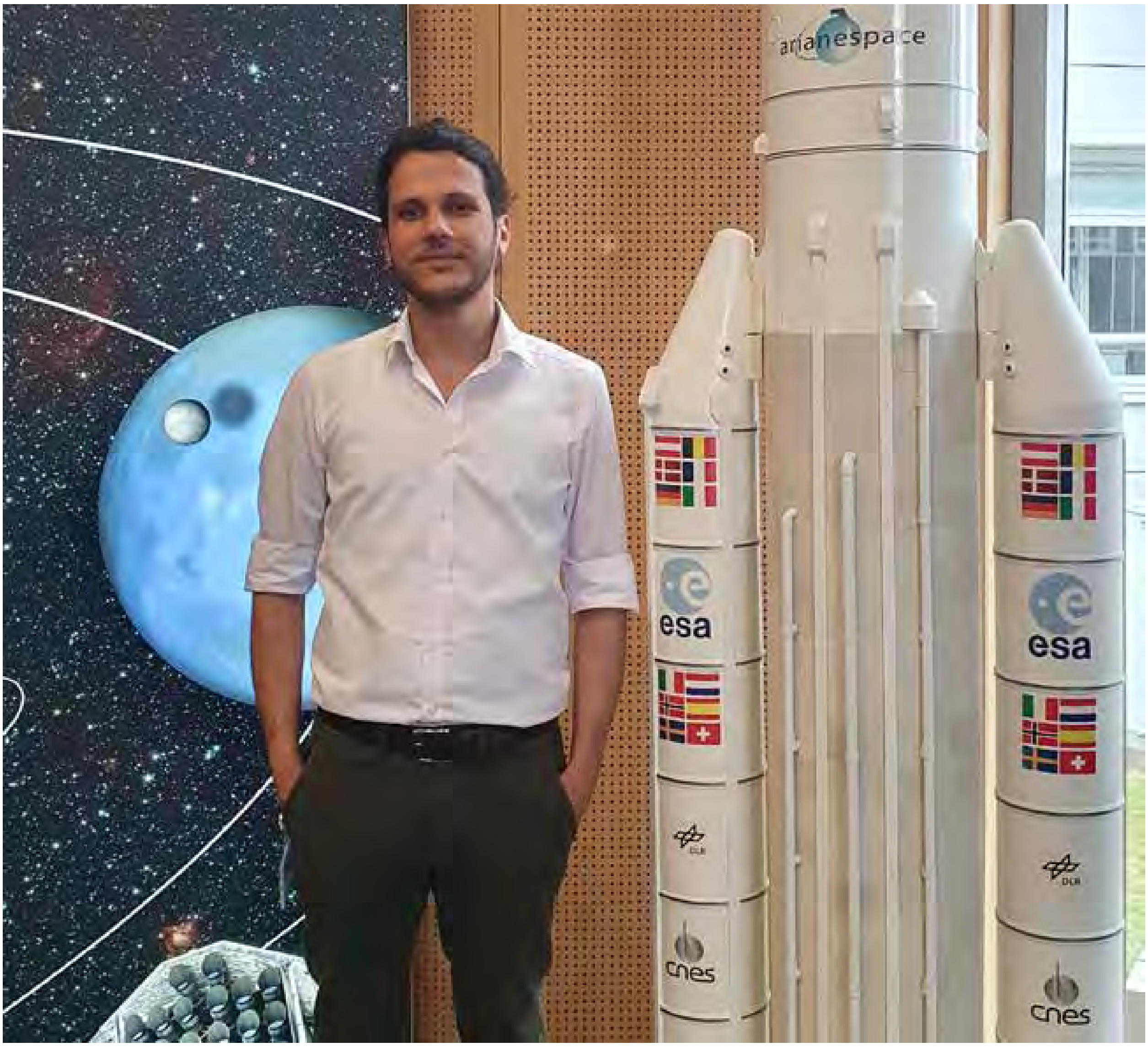
In Germany

I spent the first six months in a camp for the Syrian refugees. We were about 150 people in that camp, which was originally a fitness room before they turned it into a camp, and there I made new friends. I felt good there because I finally made it to a safe place after all the challenges that I had been through. But it was also difficult for all of us because the things that we lived through were not easy to forget. What was good was that it was very organized. There was a specific time for food and then for sleep, during which everyone was silent. Other than that, we were free to do whatever we wanted and to go wherever we wanted. There were some German people who started visiting us, to help and to listen to us. I became a friend to many of them and I am still in touch with them now.

But now I had to find a way to structure my everyday life and make myself useful. So I spent my time working as a translator from English to Arabic and at the same time I was trying to learn German. After a year and two months, I got my residency and had reached an acceptable level in the language and finished the first stage of it. Then I got a scholarship for advanced levels in German language B2, C1. Obtaining the scholarship, I still had a few months before I started the language classes and so decided to write to the geological companies for an opportunity to get an internship. After several correspondences, I was accepted to a company close to the area where I used to live and I spent three months there before stopping to complete the language course. I was incredibly happy to work in that company, everyone was nice to me and I had learned a lot from them. After I finished my final language exam, I called them again wanting to get a job there and that happened. I was accepted and started working with them and at the same time I was writing to universities to fulfil my dream finalizing my studies in Geology.

After more than a year I was finally admitted to the Technical University of Freiberg, Saxony. In Freiberg, I started a new life and I got to know a lot of friends.
Finally, after several correspondences with geological companies too, I had the chance to get a job at GKZ, whose manager invited me to a job interview, and from the first moment, I felt comfortable being there. They were very nice and striving to find out my area of interest for offering me a job opportunity. Then we were talking about the GREENPEG project, this project that immediately caught my attention. To my great joy, I was hired as a project assistant and had even found my place in an EU project.

Today Sipan Hasan lives in Berlin where he is doing his Masters in Planetary Sciences and Space Exploration. He has been a German citizen for a year and speaks fluent Arabic and German in addition to his native Kurdish, as well as English as a lingua franca.



Exploring the Geological Potential of Lithium Pegmatites in Morocco: Insights from the Sidi Bou Othmane and Zenaga Pegmatite Fields

Imad Erraji, Department of Geology, Faculty of Science Semlalia, Marrakech, Marocco

After completing my Master's degree, my passion for discovery and my desire to contribute meaningfully to scientific research motivated me to continue in academia. This decision coincided with an exciting opportunity, the launch of the "Li-RARE-Mali-Maroc" APRD project funded by the OCP foundation.
The project is hosted by the Mohammed VI Polytechnic University, and the partners include institutions from Africa (Morocco, Mali) and Europe (Spain, France, UK)*. This project, focusing on lithium (Li) and Rare Earth Elements (REEs) in natural systems such as LCT granitic pegmatites and alkaline complexes, aims to support the energy transition in Morocco by defining the geological potential of the Kingdom for rare metals.

Being part of this project provides an invaluable opportunity for hands-on research. It allows me to delve into the exploration of the geological potential of lithium pegmatites, deepening our understanding of critical minerals crucial for various industries. Furthermore, this research aligns with the growing global interest in these elements, especially in regions rich in lithium pegmatites like West Africa. The economic demand for lithium, especially in the burgeoning electric vehicle sector, highlights the importance of discovering new lithium deposits. Rare-element granitic pegmatites of the LCT family are crucial hard rock lithium sources, and exploring these could significantly boost Morocco's industrialization and economic transformation.

This is particularly relevant because presently there are no lithium or REE deposits in Morocco, but the geology of some regions is appropriate for the presence of resources in lithium as well as in REE. This is the case of the granitic pegmatites of the Taznakht inlier in the Anti Atlas and the Sidi Bou Othmane region in the Jebilet Massif for lithium. The alkaline complexes of the Awserd region in the Moroccan Sahara or the Central High Atlas are suitable for REE mineralization (Fig. 1). This synergy could position Morocco as a key player in the global battery market, driving local industry growth, job creation, and technological advancements.

In Morocco, granitic pegmatites are mainly found in the Precambrian inliers of the Anti-Atlas, north of the west African craton, and in the Paleozoic inliers of the Meseta, which represents the southern prolongation of the Variscan belt of Europe (Fig. 1). Among these, the Zenaga pegmatites in the Anti Atlas, and the Jebilet pegmatites in the Meseta stand out for their economic potential for lithium. The Zenaga pegmatites, discovered in 1936, have been the subject of an intense exploration leading to the discovery of mineralized lenses containing beryl and muscovite, and traces of columbite-tantalite.

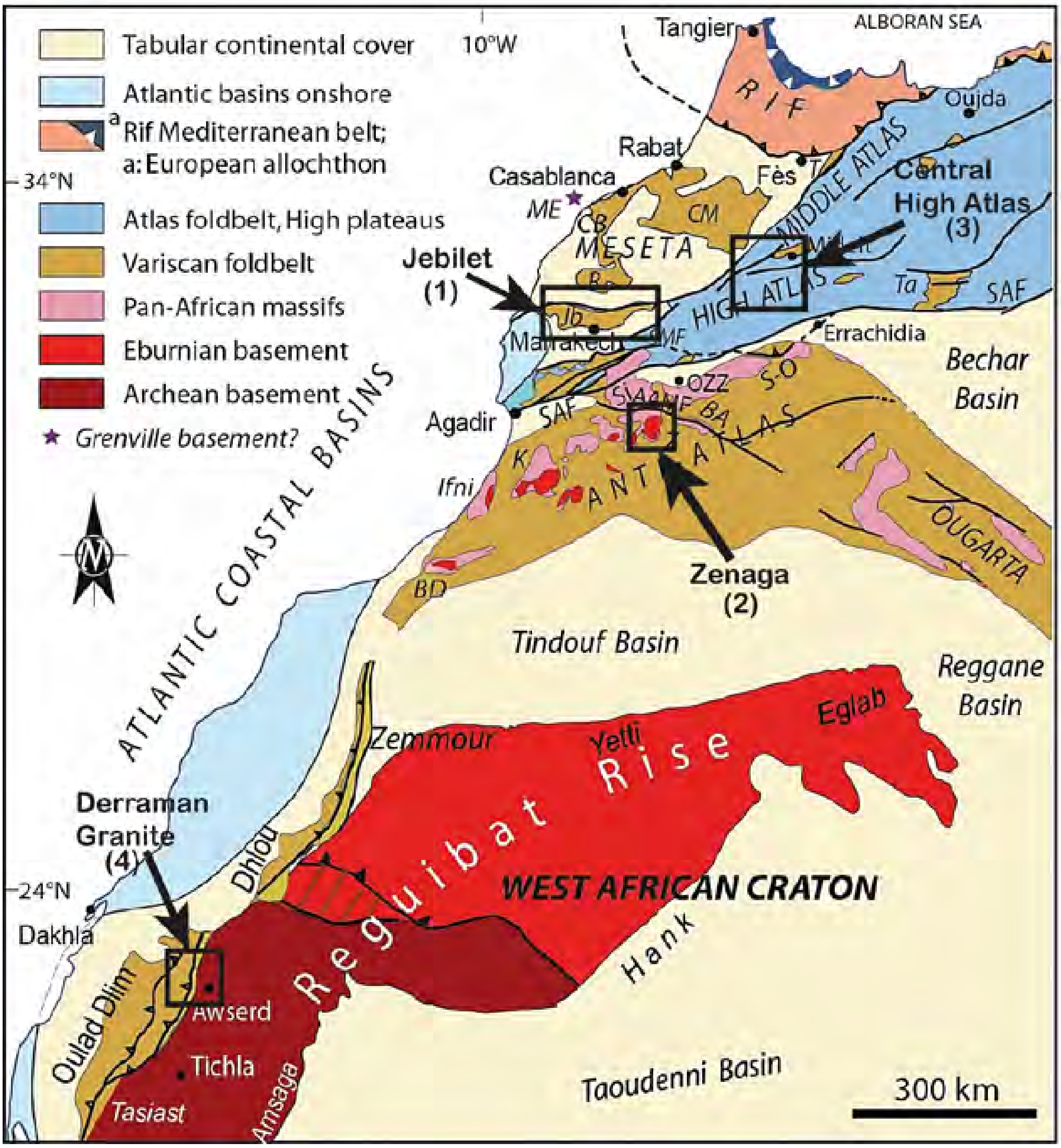


Figure 1: Location in the tectonic map of Morocco of the regions suitable for Li (1: Jebilet, 2 Zenaga) and REEs mineralisation (3: Central High Atlas, 4: Awserd)

These pegmatites have yielded significant quantities of beryl, muscovite and feldspar, while numerous phosphates, including triphylite, tavorite, ferrisicklerite and montebrasite, have been described. Recently, geochemical and petrogenetic studies have indicated that the Zenaga pegmatites are derived from peraluminous magmas. They are associated with S-type granites emplaced during late stages of the Eburnean orogeny (~ 2000 Ma). These pegmatites have been classified as rare element pegmatites, specifically belonging to the LCT family of the beryl-columbite-phosphate subtype.

Conversely, the Sidi Bou Othmane pegmatite field in the Jebilet Massif exhibits intriguing similarities with lithium pegmatites of the Variscan belt of Europe. These similarities extend to their geological processes, mineral compositions, and potential economic significance, owing to their formation within the Variscan orogeny during the Paleozoic era. The Sidi Bou-Othmane pegmatites form a subvertical dyke swarm intruding cordierite and andalusite-

bearing micaschists. The thickness of these pegmatites ranges from a few centimetres to 4-5 meters, and their extension can reach several hundreds of meters. The main minerals are quartz, feldspars and muscovite, whereas the accessory minerals include schorl, garnet, Nb-Ta oxides, lepidolite, elbaite, cassiterite, apatite, Fe-Mn and Li-Al phosphates.
A field trip was organised in June 2023 to visit the Sidi Bou Othmane and Zenaga pegmatites. The trip involved a team of national and multinational researchers, including Professor Abderrhaim Essaifi, Rachid Zayane and Ahmid Hafid from Cadi Ayyad University, Encarnacion Roda-Robles and Alfonso Pesquera from University of the Basque Country (UPV/EHU), Fauzya Haissen from Hassan II University and M'hammed El Janati from Mohammed V University. This diverse team provided a unique and first-hand experience and brought a wealth of knowledge and expertise to the exploration of these geological formations.

Figure 2: The project team at a pegmatite in the Sidi Bou Othmane area during the field trip

The Zenaga pegmatites exhibit a range of scales from centimetre to decametre lenses within micaschists and granites. These pegmatites are primarily composed of quartz, feldspars, and muscovite, with accessory minerals such as tourmaline, beryl, garnet, and phosphate masses. The pegmatites display a typical zoning pattern, with a mica-rich zone at the borders, a quartz core, and a quartz-feldspathic zone in between.

The field trip was extremely informative, especially for the Sidi Bou Othmane pegmatites. It was during this expedition that we identified several accessory minerals. These include montebrasite and columbite group minerals (Fig. 4a). Additionally, we observed that the pegmatites of Sidi Bou Othmane can be classified into different types based on their mineralogical characteristics. This extensive categorisation process took several months as I was mapping all the veins present in the field. This led to the discovery of new accessory minerals such as lepidolite and elbaite (Fig. 4b-c). In the end we classified the pegmatites into eight different types:

1) pegmatites that are poor in accessory minerals; 2) schorl-rich; 3) schorl-garnet-rich;
4) garnet-rich; 5) Fe-Mn phosphate-rich; 6) green tourmaline-rich;
7) Fe-Mn- + Li-Al-phosphates and Nb-Ta-oxide-rich; and
8) lepidolite-elbaite-rich pegmatites.

Figure 3: A large pegmatite in the Zenaga inlier. The intermediate part has been mined, only the quartz core remains.

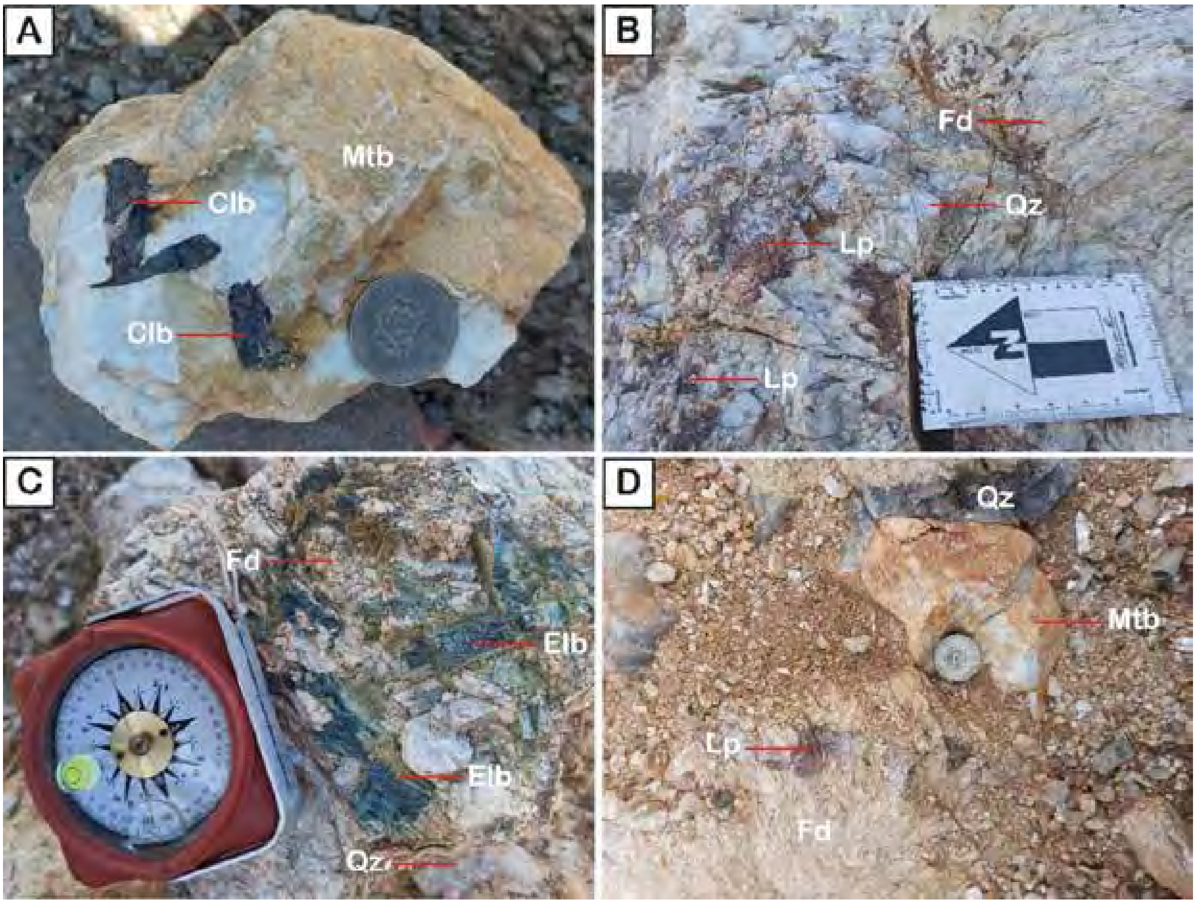


Figure 4: Photos showing some accessory minerals from the pegmatites of Sidi Bou Othmane. Qz : Quartz, Fd : Feldspath, Mc : Muscovite, Mtb : Montebrasite, Clb : columbite, Elb : Elbaite, Lp : Lepidolite

The analysis of the distribution of these different pegmatite types allowed us to define a regional zoning in the Sidi Bou Othmane pegmatite field. This zoning is characterised by an evolution from barren pegmatites containing schorl and garnet (types 1 to 4), to intermediate pegmatites characterised by the abundance of Fe-Mn phosphates (types 5 and 6), and finally to fertile pegmatites containing Li-rich minerals (types 7 and 8). The exploration and study of the Zenaga and Sidi Bou Othmane pegmatites have provided invaluable insights into the geological and mineralogical diversity of the Moroccan pegmatites.

The identification of different lithium-bearing minerals and the classification of pegmatites based on their mineralogical characteristics contribute to a deeper understanding of their geological context and potential economic significance. Overall, the collaborative efforts of national and multinational researchers, combined with extensive fieldwork and detailed mineralogical analyses, have enriched our knowledge of the Moroccan pegmatites. These findings not only contribute to scientific research, but also have practical implications for sustainable resource management and mineral exploration strategies in Morocco. Currently, Morocco is in a metal-living transition. Its strategy, outlined in the Plan Maroc Mines 2021-2030**, focuses on non-phosphate mining, good governance, sustainability and economic integration. These efforts enhance mining capabilities and support broader economic growth. Africa's rich resources and Europe's demand for safe, sustainable raw materials create a mutually beneficial relationship, encouraging investment, technology exchange and market expansion.

* https://sites.google.com/um5r.ac.ma/lithiummorocco/organisation-du-projet/membres-impliqués.

** https://www.mtedd.gov.ma/index.php?option=com_content&view=article&id=17
:strategie-nationale-de-la-transition-energetique&catid=25&lang=en&Itemid=452

European Domestic Supply

Gravel, one of the few raw materials in which the EU is self-sufficient. Nevertheless, there are major differences in availability with regard to the distance to the consumer. Gravel and sand play a crucial role in the expansion of critical infrastructure and renewable energies (for concrete production

Potential and framework for critical raw materials production in Norway

Henrik Schiellerup, Geological Survey of Norway (NGU), Trondheim, Norway

Norway is located on the western margin of the Baltic Shield and shares a geological history with Sweden and Finland. The position on the outbound side of the shield is reflected in a resource potential unique to Norway, but also to some extent shared with Sweden and Finland. The Fennoscandian countries represent one of the most prolific European regions in terms of current mineral production, and the combined Nordic endowment has a profound potential for supplying European industry with critical raw materials in the future (Eilu et al., 2021).

Production

Norway has a considerable mineral industry extracting metallic ore, industrial minerals, natural stone and aggregates. Current production includes iron ore and titanium minerals, as well as natural graphite, quartz and quartzite, nepheline syenite and other feldspar minerals, olivine, limestone/marble and dolomite (Figure 1). For certain commodities, Norway plays a significant role in the European raw materials supply chain.

Part of the Norwegian production represents commodities which are considered critical raw materials by the EU commission at the extractive stage, such as natural graphite and nepheline syenite, whereas others may be refined to become EU critical commodities at the processing stage, such as titanium metal and elemental silicon. Some again are considered critical in other major economies, such as titanium minerals in the US. The Norwegian processing industry is an important supplier of processed critical raw materials, such as nickel, cobalt, copper, silicon and aluminium.

Both natural and synthetic graphite are included in the EU list of critical raw materials (EU, 2024). The Trælen deposit (Figure 2) on the island of Senja in Northern Norway is the World's highest-grade operating flake graphite mine with a current mill feed grade of 28% (Mineral Commodities, 2023). With a nameplate capacity of 10 000 tons per year, Trælen is the most important producer of natural crystalline graphite in Europe, and the host region remains highly prospective. In addition, a Norwegian production of anode-grade synthetic graphite is under development (Vianode, 2024).

Feldspar minerals, including feldspathoids, attained status as critical raw materials in 2023, and Norway is the main supplier of nepheline syenite to the EU (SCREEN, 2023). Quartz and quartzite are extracted at five localities in Norway (Directorate of Mining, 2024), and part of the Norwegian production is nourishing a domestic silicon industry. As a result, Norway supplied the EU with 35% of all imported silicon in 2016-2020 (SCRREEN, 2023).

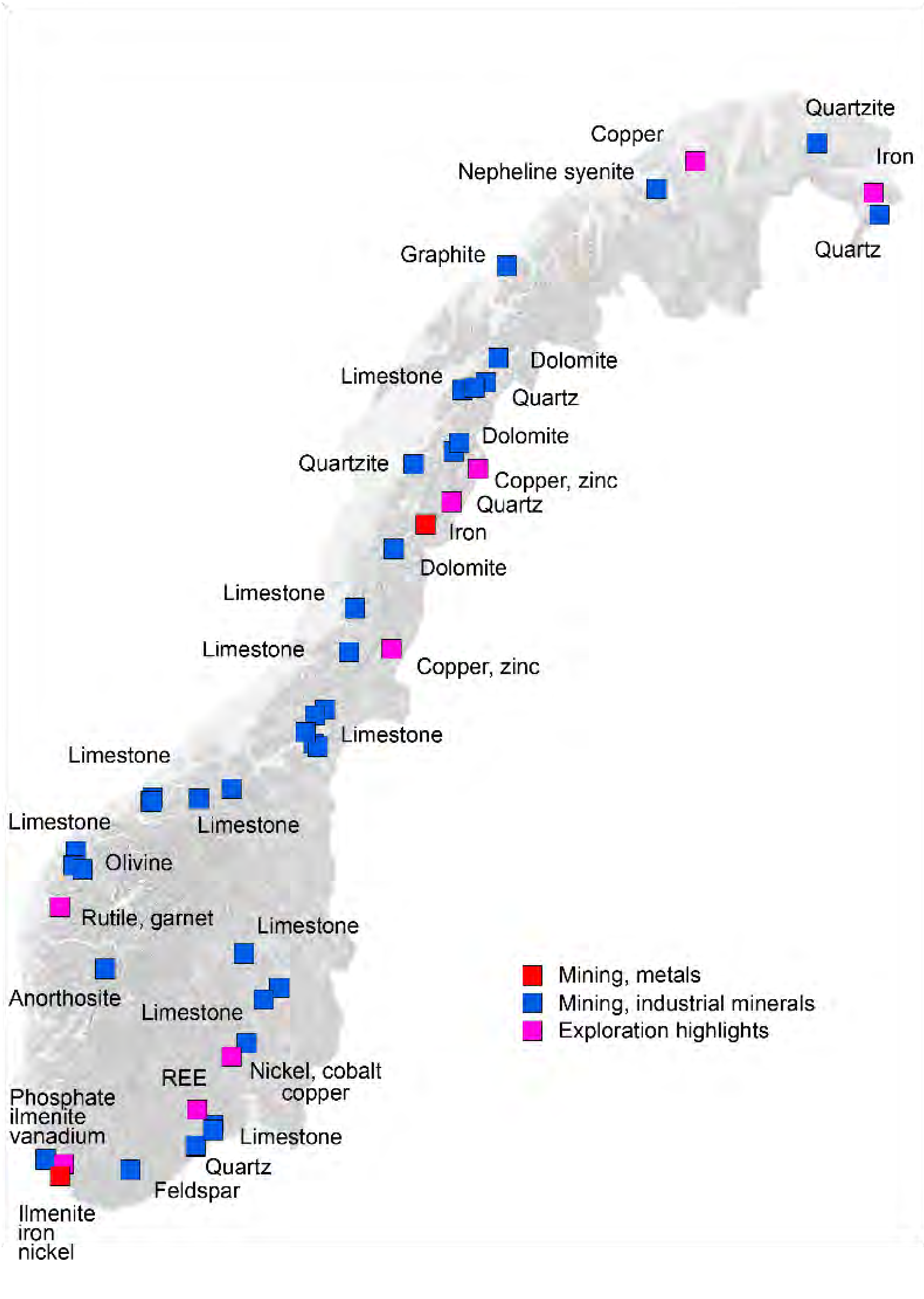


Figure 1: Exploration highlights and current production in Norway. Figure based on data from the Directorate of Mining and the Geological Survey of Norway.

Figure 2: The Trælen mine on the Island of Senja in North Norway is currently the World's highest-grade operating flake graphite mine. Photo: Janja Knežević Solberg.

The Norwegian production of titanium minerals constituted 4.7% of the global production in 2023, measured as titanium dioxide (USGS, 2024). Current production is limited to the Tellnes hard rock ilmenite mine in Southwest Norway. A new mine at Engebø in Western Norway will commence production in 2024, extracting rutile and garnet from eclogite (Figure 3). The production will significantly increase the Norwegian output of titanium minerals.

Exploration and developments

A string of projects is about to complete or have completed their scoping studies, and a couple of projects have advanced to more mature stages. A mining concession has been awarded to re-open the Sydvaranger iron mine close to the border with Russia, but otherwise most of the advanced projects are dealing partly or fully with critical raw materials, or raw materials that are needed as feedstock for critical materials at the processing stage. The Nussir copper deposit in North Norway also has a mining concession in place (Directorate of Mining, 2024).

Figure 3: Ongoing construction at the Engebø rutile and garnet deposit. Production ramp-up is planned for Q4 2024, eventually reaching 35 kt TiO_2 per year. Photo: Nordic Mining.

In Southwest Norway, a major project targeting phosphate, titanium minerals and vanadium-rich magnetite is advancing east of Egersund. Resources of rare earth elements have been documented in the Fen deposit south of Oslo, clearly demonstrating that this carbonatitic deposit is continental Europe's largest known resource of light REE's. Notable brown field projects include Cu-Zn mining camps in Joma and Sulitjelma in Central and Northern Norway, and the nickel-copper-cobalt project at Ertelien in South Norway.

For industrial minerals, the high-purity quartz project at Nasafjell in Northern Norway should be mentioned as a possible feedstock for silicon production. Additional critical commodities being targeted by earlier stage commercial exploration include natural graphite, beryllium and platinum group elements.

Framework

Norway is the European country with the highest rate of renewable energy in the domestic power grid. Hydropower is the main power source and is used in part to drive an energy intensive Norwegian processing industry. The potential for supporting and developing sustainable raw materials supply lines is therefore considerable. Electricity production and transmission is integrated with Nordic and European energy markets, and almost all Norwegian natural gas is exported. According to the Norwegian Ministry of Energy, 30% of UK and EU gas imports are currently derived from Norway.

In 2023, the Norwegian government published a new Mineral Strategy (Norwegian Ministry of Trade, Industry and Fisheries, 2023) with an aim to increase sustainable production of critical raw materials through a stronger and better framework for mineral exploration and production. The mineral strategy is one of several policies and legal documents aimed to ensure green industrial development in the coming decades.

Norwegian policy development is engrained in a geopolitical context, where trade partners and allies play an important role in bringing raw materials to political and industrial attention. The Norwegian government has formalised bilateral agreements with both the EU and individual European countries, as well as the US, to align industrial policies and promote the country's resource potential. Currently, the most important action in the Norwegian mineral production framework is the eventual adoption of EU's Critical Raw Materials Act, which was enforced in the EU member states in May 2024.

References

Directorate of Mining with the Commissioner of Mines at Svalbard 2024. Harde fakta 2023. https://dirmin.no/sites/default/files/harde_fakta_2023.pdf

Eilu, P., Bjerkgård, T., Franzson, H. et al. 2021. The Nordic supply potential of critical metals and minerals for a Green Energy Transition. Nordic Innovation Report. https://norden.diva-portal.org/smash/get/diva2:1593571/FULLTEXT02

EU 2024. EU regulation 2024/1252 of the European Parliament and of The Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202401252

Norwegian Ministry of Trade, Industry and Fisheries 2023. Norwegian Mineral Strategy. https://www.regjeringen.no/contentassets/1614eb7b10cd4a7cb58fa6245159a547/norges-mineralstrategi_engelsk_uu.pdf

Mineral Commodities 2023. MRC Mineral Commodities ltd. Annual Report 2023. https://www.mineralcommodities.com/wp-content/uploads/2024/04/Annual-Report-2023.pdf

SCRREEN 2023. Updated fact sheets, 2023. https://scrreen.eu/crms-2023/

USGS 2024. U.S. Geological Survey, Mineral Commodity Summaries, January 2024. https://pubs.usgs.gov/periodicals/mcs2024/mcs2024.pdf

Vianode 2024. https://www.vianode.com/. Accessed July 2024.

Lithium BATTERIES NOT INCLUDED - more than a battery metal

Brendan Clifford, Co-CEO Mota Ceramic Solutions (MCS), Oia, Portugal

Introduction

When history remembers the 21st Century it will be as a step change in the transition to a low carbon economy and with it the relative importance, demand and availability for new and old minerals - lithium is one such material.

As a multi-mineral mining and processing company Mota Ceramic Solutions (MCS®) considers itself a responsible, purpose-led Group with its philosophy encapsulated in its corporate slogan 'Minerals for Life'. This phrase is intended to remind everyone that natural mineral-based resources are vital for the quality of life in society today, but also its responsibility for the stewardship of scarce, dwindling mineral resources.

Established in 1967, FELMICA is an MCS® subsidiary with 20 feldspar and quartz concessions in Portugal, of which 9 are lithium-bearing pegmatites. In the literature, FELMICA is often referred to as the only, or one of the few, 'lithium producing companies in Europe...' This is misleading when one recognises, although it produces lithium-bearing feldspars, it does not per se produce lithium and is not directly involved in feeding Europe's energy transition.

Whilst the Group is aware of the EU's ambition to develop an end-to-end 'Made-in-Europe' lithium value chain; MCS® primary raw materials business focuses on supplying mineral solutions for ceramics, glass and other applications.

MCS® challenge is to develop appropriate strategies to maximise the value of the mineral resources at its disposal and thus the strategic decisions it takes. Until now, two factors have led MCS® to take a decision to follow a 'batteries-not-included' strategy:

1. Whilst lithium is vital for batteries, it is also a versatile material used in a wide range of other applications
2. The risks associated with technological challenges, financial commitment, political uncertainty and anti-mining sentiment from local communities cannot be ignored

Even so, there are a lot of moving parts which will impact the speed of new lithium project development in Europe and elsewhere. Thus, MCS® stays abreast of these developments to ensure the company, if or when appropriate, can take advantage of new business opportunities in the lithium space whilst minimising the threat to its traditional customer base.

Lithium production shift

Several years ago, Goldman Sachs described lithium as 'the new gasoline' and in 2017 with this level of hype market expectations about future demand led to major investment in lithium exploration. At that time production capacity of Lithium Chemical Equivalent (LCE) was 43,000 tonnes per year. By 2021 there was a lithium deficit and unprecedented year-on-year price increases saw lithium chemical prices quadrupled - up 443%[1] and flurry of industry mergers and acquisitions.

Since that time the lithium spot price index peaked at 1,343 at the end of 2022, but at the start of 2024 had fallen back to 328[2] as new refining capacity has come on stream. Nevertheless, the massive global demand for lithium, which is vital for electric vehicle (EV) and battery storage is now forecast to grow almost 1000% to 415,000 tonnes relative to the 2017 benchmark and continue to move its availability away from traditional applications[3].

Associated with this demand forecast, Europe wishes to develop its own lithium battery supply chain to reduce dependence on imports, shorten supply chains, minimise geopolitical risks and threat of mineral nationalism. Despite these ambitions, Europe it is yet to create a full end-to-end (extraction, concentration, chemical conversion and assembly) battery supply chain, has limited battery-grade chemical conversion experience and no fundamental regional reserve plan to feed it - there is a clear disconnect between governmental ambition, policy and material supply availability.

It is anticipated that the release of a new Critical Raw Minerals Act (CRMA) in March 2024, with both lithium and feldspar on the list will help promote the development of local hard rock lithium resources to feed planned down steam processes for lithium-ion battery manufacture in Europe. However, the speed of development will be inextricably linked to technological development, market prices, Member State legislation and social acceptance to operate in each potential extraction area.

Sustainability & anti-mining sentiment

As well as the energy transition, a 'Green' Revolution is unfolding in the minerals sectors themselves. MCS®, like many mining and mineral processing Groups are having to navigate the increasing pressure from a wide range of stakeholder issues related to its Environmental, Social and Governance (ESG) agenda. This in turn has been driven by the accelerating demand for resources (metals, rare earths, industrial minerals, fuel, water), competition for land use as well as its impact on local communities and biodiversity.

The multi-dimensional and wide-ranging aspects of sustainability highlights the need for an increasingly collaborative approach and dialogue between industry, local communities and government to positively influence public opinion as ESG priorities.

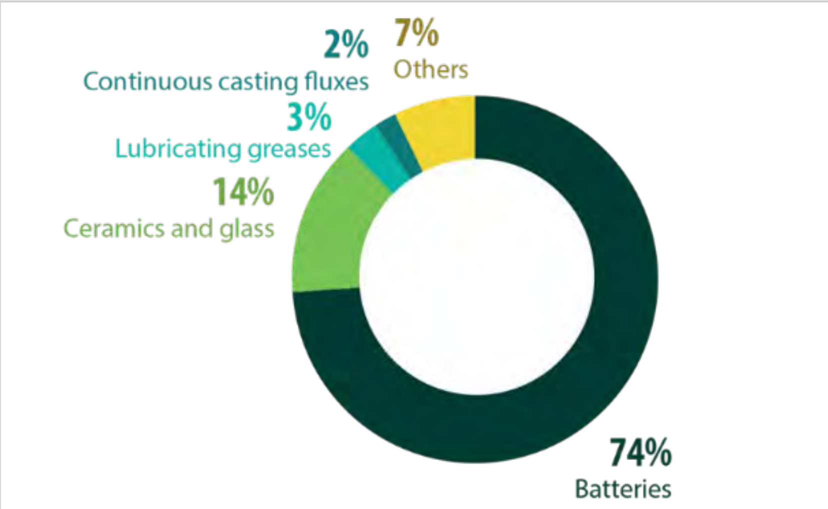
A consequence of increased environmental awareness anti-mining sentiment, whilst well intentioned, is often driven by ideological enthusiasm and misinformation and failure to address the need for balance and compromise between economic, environmental, and social concerns. The narrative needs to change and a clear message sent that the route to a net zero future and transition to a circular economy still means the need for new primary raw material resources to support the world's population growth and demand for mineral-based products, which form the hidden foundation of modern society.

Lithium - industrial applications

Whilst European governments and mineral industry focus shifts to develop its own lithium supply chain for its own energy transition, one should not forget that lithium, due to a range of unique properties, still finds commercial application in a wide range of other industries.

Consequently, as referred to above, a real shift in supply has implications for corporate strategies business model paradigms and a wide range of industry application beyond batteries.

After the demand shift in 2022, the global requirement for lithium as measured as Lithium Carbonate Equivalent (LCE) and the amount of material available for non-battery applications reduced to only 26% of total supply, most of which being consumed in the ceramics and glass sectors (14%), industrial lubricants (3%), casting fluxes (2%) and others (7%)[4] (see Figure 1).
Going forward, as lithium-ion battery technology improves, and with no immediate substitute on the horizon, the drive (no pun intended) for investment in lithium concentration and chemical conversion (lithium hydroxide or lithium chloride) projects will continue, but demand from non-battery applications, depending on the sector remain, but modest at between 2.0% - 6.6% (CAGR).



These forecasts, whilst providing a compelling case for mining companies, and other value chain supplier to look to benefit of these trends, it is also important to understand the disruptive implications and associated risks. It is also important to recognise that the lithium industry is still young and has a relatively short history on which to predict micro-demand cycles or what's next…!

Figure 1

Ceramics & Glass

For many years the ceramic, glaze and glass industries have recognised lithium as a network modifier and valuable fluxing agent. By adding lithium, in the form of lithium-bearing feldspar to ceramic and glass formulations, the 'eutectic' (melting temperature) can be lowered during sintering. Lowering the eutectic point allows ceramics and glass manufacturers to reduce kiln firing temperatures, which in turn provide energy saving and reduced CO_2 emissions.
In ceramics, lithium also improves thermal shock resistance[5] and is the additive of choice in oven-to-tableware products. If lithium is incorporated into glazes, it also enhances transparency and creates glossy surface finishes. In the case of glass, lithium improves strength, durability, chemical corrosion resistance and expansion coefficient. It can also impart unique optical properties for specialty lenses and prisms. When added as in the form of a lithium-bearing feldspar, the feldspar also provides a source of alumina. As a ceramic industry focused business, MCS® produces a range of sodium and potassium as well as lithium-bearing feldspars which are supplied to ceramic and glass end-users.

Lubricants & Greases

In addition to ceramics, glazes and glass, lithium hydroxide finds application in the production of car and aerospace lubricants where low water solubility, high resistance and adhesion to metal, viscosity, rust-inhibiting properties and stability at high temperatures are

advantageous. Lubricants are designed to reduce friction, prevent mechanical wear, and thus reduce the need for maintenance in gearboxes, engines, and vehicle transmissions.
The most popular types of lubricants are oils and greases, where grease production is estimated more than 1.1 million tonnes per year, or only 3% of global level lubricant market. Approximately 75% of these greases are incorporate lithium (lithium 12-hydroxystearate) as a thickener with some 50% used in the automotive sector and 50% in other industrial applications.

Surprisingly, electrification of vehicles, rather than reducing demand has increased demand for speciality greases in Battery Electric Vehicles (BEV), but substitution is on the agenda for many car manufacturers.

Polymer production

Polymer catalyst-n-butyl lithium (nBuLi) is produced by reacting lithium with 1-chlorobutane or 1-bromobutane (2 Li + C4H9X → C4H9Li + LiX). However, nBuLi is a substance not to be 'played with' as it is highly volatile and can ignite in air (pyrophoric) or when exposed to water. nBuLi is used as a polymerisation initiator in the production of synthetic rubbers (SR) such as polybutadiene or styrene-butadiene (C4H9Li + CH2=CH-CH=CH2→ C4H9-CH2-CH=CH-CH2Li) of which 70% of global production finds application in the manufacture of vehicle tyres.
Based on market forecasts, demand for SR over the next 10 years is expected to continue to grow at 4.5% (CAGR) and thus an on-going demand for lithium.
Interestingly a Chilean start-up is looking to recycle old tyres into components for lithium-ion batteries in the form of carbon-black.

Continuous casting mould (CCM) powders

Metal powders are employed in a broad range of applications and although relatively small volumes, serve a critical role in the continuous casting process of long steel products such a billets.
The mould fluxes are responsible for providing lubrication between the form and steel mould and control the horizontal heat transfer. The properties of these mould powders are affected by their composition and arrangement of network formers (SiO_2, Al_2O_3) and modifiers (Na_2O, Li_2O, CaO, MgO, K_2O). Lithium oxide (Li_2O) is a high-efficiency flux for adjusting the meting point and viscosity of mould fluxes.
Below a range of weight percentages of these common oxides used in conventional mould powders are shown:

wt%	Ca	Si	Mg	Al	Mn	Na	F	Li	B	Zr	Ti	Basicity
Min	22	25	0	3	0	3	0	0	0	0	0	0.7
Max	44	45	14	22	3	16	11	5	2	2	< 1	1.3

Without discussing the chemical and physical issues, lithium is chosen as it is more effective at enhancing crystallisation than sodium and when combined with boron can replace fluorspar in the casting processes. For this reason and as demand for infrastructure steel grow, the market is forecast to grow at 6.6% (CARG) over the next 5-10 years along with the demand for lithium.

Other application for Lithium

Without going into specifics, lithium also finds application in the form of lithium silicate sealers and densifiers applied to the surface of the concrete, where they react with the calcium hydroxide to form a dense, hard, and waterproof surface thus improving strength, durability, and appearance.
Certain lithium compounds, also known as lithium salts, find use in pharmaceuticals, specifically mood stabilising medicine.
As lithium carbonate and lithium fluoride is used in aluminium electrolysis whilst lithium chloride and lithium bromide are used in air treatment and lithium metal in alloys primarily for weight advantages. All the above reinforce the fact that lithium is much more than just a battery metal…!

Implications of hard-rock Lithium production In Europe

Whilst MCS® has adopted a 'batteries NOT included' strategy in favour of supplying other industry sectors, this does not mean it can ignore the implications of the developments taking place in the lithium space across Europe.
Globally hard-rock lithium sources overtook brines as the principal source of lithium in 2018 and this is likely to grow in Europe due to the occurrence of lithium-bearing pegmatites.
Today, whilst some 90% the major hard-rock lithium concentrate comes from Australia and Chile and exported to China for processing, it is estimated that if several of Europe's planned lithium mining projects proceed, they could allow the EU to source up to 30% of its own lithium demand by 2050. Whilst it is likely to take the rest of the decade to reach capacity, research suggests even if all mines in the pipeline on stream with right battery-grade specification, there could still be a shortfall in 2030[6].

The Finnish and Portuguese lithium concentration projects are the most advanced, but France and the UK have entered the race joining Germany, Czech Republic, Austria and Spain.
Given the mineralogy and nature of the deposits, ANY of the European hard rock liberation processes will generate feldspar and quartz by-products. Given the volumes involved, they have the potential to be disruptive to traditional ceramic and glass mineral supply chains and should not be underestimate - a game changer for the industry if new sources of feldspar and quartz flood the market…!
Other factors that will influence future feldspar market demand/supply include market demand, logistic costs, new process technology, mineral sovereignty and legislation.

Conclusion

History will remember the 2020's in Europe as a time of step change in the transformation to low carbon economy and European focus on its own mineral security for critical and strategic raw materials.
Despite rapidly changing battery technologies, lithium is expected to remain the default power pack solution for electric mobility and stationary electrical storage for the foreseeable future.
Whilst lithium is in high demand for energy transition, one should not forget Europe still has NO local lithium supply chain.
Whilst challenging times for all, it is important to recognise that to overcome the diverse range of complex and rapidly changing priorities, multiple industry stakeholders' need to increasingly work in partnership to find solution if lithium-bearing mineral extraction is to grow in Europe.
Given lithium's unique properties, it makes it a versatile material in ceramics and other applications and demand for lithium will continue to impact other traditional applications for lithium and pegmatite exploitation has potential disruptive implications for business paradigms and corporate choices.
Despite its own 'batteries-no-included' strategy, MCS® remains optimistic that it can play its part in the development of a European lithium ecosystem whilst continuing to provide access to this versatile, and often-misunderstood material, for traditional and new applications.
Finally, one should not forget the words of the American environmental scientist Donella Meadows (March,1941 - February 20, 2001) who wrote… "*the scarcest resource is not oil, metal, clean air, capital, labour or technology, but our willingness to listen and learn from each other and seek the truth rather than seek to be right*…"

References

[1] Battery Metals Review Magazine

[2] Wood MacKenzie

[3] World Bank

[4] USGS, Mineral Commodity Summary 2022

[5] Thermal shock resistance refers to a material's ability to withstand sudden temperature changes without cracking

[6] S&P Global Commodity Insight

The Nordic European countries – mining potential and legislation

Mathias Forss, CEO, GeoPool Oy, Vantaa, Finland

Overview

Sustainable mineral production is critical for advancing decarbonization and strengthening European economies. Key to developing industrial value chains in energy, mobility, and digitalization, these materials are essential for Europe's sustainable supply chains and increased domestic production. The Nordic countries—Norway, Sweden, and Finland—are geologically positioned within the Fennoscandian Shield, a mineral rich region with significant raw material resources. This shared geological heritage endows these nations with extensive resource potential substantially contributing to Europe's demand for critical raw materials. As these countries continue to develop their mineral industries, they will play a key role in ensuring a stable and diversified supply of materials for future technological and sustainable advancements.

Sweden's Role

Sweden plays a significant role in Europe's mineral production landscape. It has extensive iron ore deposits in Kiruna and Malmberget and produces substantial quantities of copper, zinc, and lead in Vasterbotten district and in Bergslagen. Also outside these region is an increase in mineral exploration for critical minerals. A remarkable breakthrough has occurred with the discovery of Europe's largest rare earth element deposit in Kiruna published in early 2023.
In parallel, exploration initiatives are intensifying in the Northern Sweden and in the Bergsslagen area focused on uncovering new deposits of lithium. Sweden's mineral industry is well-established, with a focus on extracting various metallic ores and industrial minerals. Current production and exploration include:

- **Iron Ore**: Sweden is a major global producer of iron ore, with the Kiruna and Malmberget mines being central to its output.
- **Copper and Zinc**: The Garpenberg mine produces significant quantities of copper and zinc. And several mines in the Vasterbotten district.
- **Lead**: The Zinkgruven mine is a major source of lead and Zink in Sweden.
- **Rare Earth Elements**: The Norra Kärr deposit contains substantial rare earth reserves.
- **Lithium**: Sweden is developing new lithium projects to support green technologies. Mainly along historically known districts of pegmatites, such as in the Bergby area, in Bergslagen, but also elsewhere in Sweden.

In parallel, exploration initiatives are intensifying in the Gold Line Belt, where efforts are focused on uncovering new deposits of lithium and gold.

Finland’s Role

Finland is situated within the Fennoscandian Shield, sharing geological characteristics with Sweden and Norway. This location contributes to Finland's substantial mineral resources, which include significant reserves of nickel, copper, cobalt, rare earth elements, and lithium.
Finland's mineral resource management is not a one-time event, but an ongoing process, driven by a series of impactful developments. At the forefront is a major gold, nickel, copper, gold, platinum and palladium mining operation in Northern Finland. In addition, there is continuous mining for nickel, zinc, cobalt, copper, and apatite in Finland outside the Lapland region. These ongoing operations are substantially boosting the country’s mineral output, enhancing Finland’s position in the global gold market and contributing significantly to the national economy. In addition to gold, several development projects are underway to extract valuable resources such as nickel, cobalt, copper and lithium. These initiatives reflect a strategic effort to tap into critical minerals that are essential for various high-tech and green technologies. By advancing these projects, Finland aims to strengthen its resource base in line with the Finish mineral strategy and European Critical Raw Materials Act.
The furthest advanced lithium project is the Keliber project in Ostrobothnia, western Finland. There are several regions of historically mapped pegmatite occurrences outside Ostrobothnia, such as southern, eastern, and northern Finland. Several explorers are not only evaluating if these are lithium bearing but also exploring for new historically unknown pegmatites. Knowledge about pegmatites is rapidly increasing; new discoveries are made continuously. Once new pegmatites are discovered the next stage is to find out the extension of the lithium mineralisation. The GREENPEG findings provide a valuable toolset to support exploration companies in this work.

Finland holds a robust mineral industry with ongoing extraction of a variety of metallic ores and industrial minerals. Current production includes:

- **Nickel and Copper**: Significant operations such as the Kevitsa mine produce large quantities of nickel and copper, along with platinum group metals.
- **Gold**: The Kittilä mine is one of Europe’s largest gold producers.
- **Zinc and Cobalt**: The Talvivaara mine is a major source of nickel, zinc, and cobalt.
- **Apatite**: The Siilinjärvi mine provides phosphate for fertilizers.
- **Other Minerals**: Production also includes graphite, talc, and feldspar minerals.

Finland has a well-developed infrastructure for the processing of various raw materials, contributing significantly to its economy and the broader European supply chain close to ports in Kokkola, Harjavalta, and also in Siilinjärvi. Finland plays a crucial role in the European raw materials supply chain, particularly in the production of critical materials like nickel, cobalt, and rare earth elements. Some Finnish commodities are critical at the extractive stage, such as nickel and cobalt, while others are refined into critical raw materials, such as lithium. Finland’s processing industry is also a significant supplier of refined products like silicon and aluminium. The energy supply required is mainly from nuclear, but usage of biomass, wind- and hydropower is increasing. Finland has a good electrical power grid maintained to support the processing facilities with renewable energy.

Investment Focus Areas

In today's dynamic mineral sector, several key trends are shaping the future of exploration and investment. There is a marked emphasis on critical minerals essential for emerging technologies, particularly those required for electric vehicles and renewable energy systems. This focus highlights the growing importance of these resources in driving technological advancements and supporting sustainable energy solutions. However, albeit the trend for investments in critical minerals mining critical raw materials only encompasses only 2% of global mining. Technological advancements play a pivotal role in this evolution. Enhanced exploration technologies, such as remote sensing, improved geophysical data acquisition such as invented by GREENPEG project as well as machine learning, are significantly improving efficiency and accuracy in locating valuable deposits and lower the environmental impact. These innovations are helping to streamline exploration processes, make exploration more environmentally friendly and reduce associated costs.

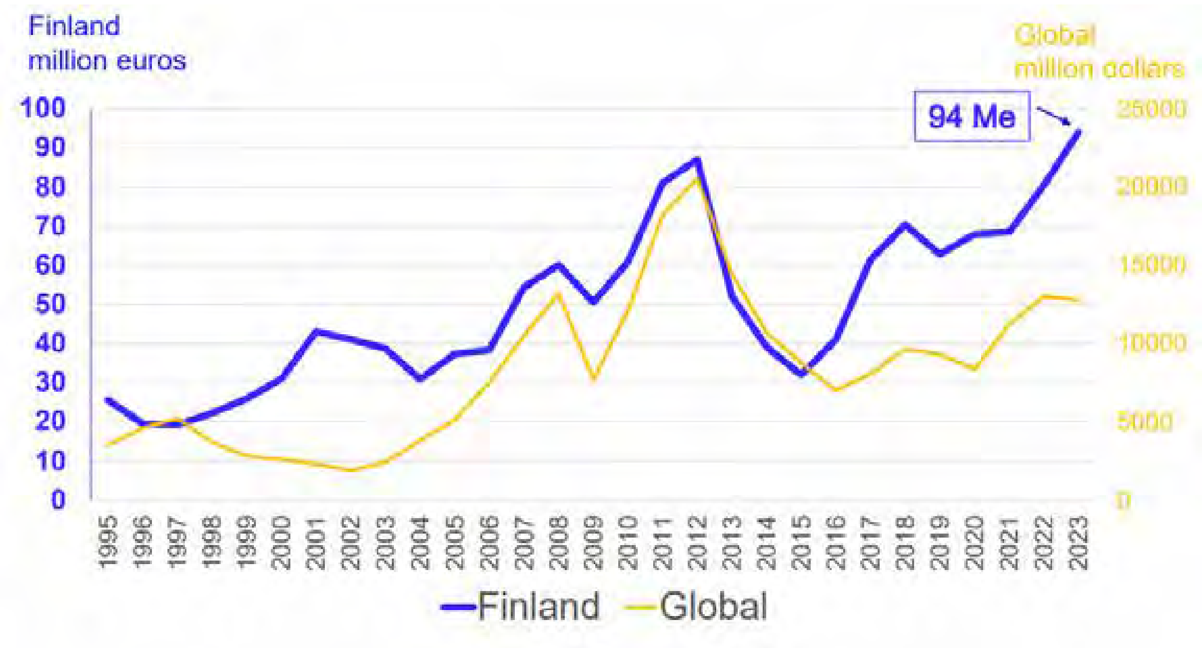
Sustainability and environmental, social, and governance (ESG) considerations are increasingly influencing investment decisions. Investors are now placing greater emphasis on practices that align with environmental protection, social responsibility, and sound governance, reflecting a broader commitment to sustainable development in the mineral sector.
Geopolitical factors also play a crucial role, with trade tensions, relocation of supply chains and global political dynamics steering investments towards stable and favourable regions. This trend underscores the importance of strategic positioning in a volatile global landscape.

Mining practices are becoming more prominent, with investments directed towards methods that minimize environmental impact. This shift is in line with the global push for more sustainable and eco-friendly mining operations by the project owners and the given framework conditions by policymaking, such as the European Critical Raw Materials Act.
Furthermore, there is a growing trend of investment in junior exploration companies, which, despite their higher risk, offer significant potential rewards. These small, innovative firms are seen as key players in discovering new resources and advancing exploration techniques. Investors are diversifying their portfolios to mitigate risks associated with commodity price fluctuations. This strategy helps balance potential returns with the inherent volatility of mineral markets, ensuring more stable investment outcomes.
The global trends in investments follow a pattern:

- **2010-2013:** A post-recession recovery led to increased global exploration budgets, peaking at nearly $20 billion by 2012 and almost 90M€ in Finland.
- **2013-2016:** A downturn in commodity prices reduced exploration budgets to around $7.5 billion by 2016 globally and 30-40M€ in Finland.
- **2017-2019:** Renewed interest in battery metals increased exploration budgets to approximately $11 billion by 2019 globally and 60-70M€ in Finland.
- **2020-Present:** The COVID-19 pandemic initially disrupted exploration but was quickly adapted to. Investments surged to over $13 billion in 2022, driven by the green energy transition and a focus on sustainable mining. Notable is that investment in Finland continues to increase to a top investment record in 2023.

Investments in the Nordic Countries - Nordic Advantages

With its rich reserves of base and precious metals, as well as industrial and critical minerals, the Nordic region is a key player in the mineral sector. It offers a stable political environment, transparent regulations, aiming to secure the supply within Europe with high governance standards. These aspects make the region attractive to investors. The region's strong focus on sustainability aligns with global green mining trends.
In the figure below comparison of investments in ore exploration made in Finland and globally to illustrate the attraction for the Nordic countries (www.tukes.fi). What is interesting is the increase in investments in Finland gopared to globally since 2016 onwards.



Legislation updates in the Nordics

In recent years, Nordic countries have taken significant steps to enhance mineral exploration and update their legislation to support sustainable mining practices. Here's an overview of the actions and updates from Norway, Sweden, and Finland:

Norway

Legislative Updates

- Mineral Act (2009): Norway has a comprehensive Mineral Act that governs the exploration and extraction of mineral resources. This Act was updated to ensure sustainable practices and environmental protection. In addition Norway has set out an new minerals strategy that is designed to sustainably harness its geological wealth, support economic growth, and contribute to the global supply of critical raw materials. By focusing on innovation, sustainable practices, and international cooperation, Norway aims to become a key player in the minerals sector, supporting the transition to a green and sustainable economy.
- Deep-Sea Mining Regulations: Norway is developing specific regulations for deep-sea mining in the Arctic, focusing on minimizing environmental impacts and ensuring sustainable operations. This could be a long-term advantage in being a

Strategic Partner in the EU Critical Raw Mateials Act as the European Commission doesn´t want to recognise deep sea mining projects as Strategic Projects before the effects of deep-sea mining on the marine environment, biodiversity and human activities are sufficiently researched, the risks are understood and technologies and operational practices are capable of demonstrating that the environment is not seriously harmed.

Sustainability Initiatives

- Green Transition: Norway has focused on integrating green technologies and reducing the carbon footprint of mining operations. This includes advancements in processing technologies and exploration of rare earth elements.
- Research and Development: Norway supports R&D projects related to sustainable mining and mineral processing, including new facilities for synthetic graphite production.

Government Support

- Funding and Incentives: The Norwegian government provides financial support and incentives for exploration projects that align with sustainability goals and technological innovation.

Sweden

Legislative Updates

- Mining Act (1991): Sweden's Mining Act has been under review to address environmental concerns and ensure that mining activities adhere to sustainable practices.
- In 2023, the Swedish government introduced a new mineral strategy aimed at increasing sustainable production and improving the regulatory framework for mineral exploration and production. This strategy is part of a broader set of policies designed to foster green industrial development and support Sweden’s role in the European and global mineral markets.
- Sweden’s policy framework emphasizes aligning with European and international standards to promote sustainable resource management. Additionally, Sweden’s mineral strategy focuses on enhancing collaboration with international partners and stakeholders to strengthen its position in the global minerals market. The strategy highlights balancing economic growth with environmental responsibility, ensuring that Sweden’s mineral production aligns with national and European goals for sustainability and strategic autonomy.

Energy Policy

- Uranium Mining Ban: Sweden is considering lifting the ban on uranium mining to enhance its role in supporting nuclear energy, which is part of the country's broader energy strategy.
- Sweden has a strong hydroelectric power for renewable energy sources, and increasing windpower and biomass production.Additionally, Sweden is taking a forward-looking stance on nuclear energy by planning to lift its uranium mining ban. This policy shift is aimed at bolstering Sweden’s role in supporting nuclear energy, which Sweden regards essential for a low-carbon future.

Sustainability Initiatives

- Climate Goals: Sweden has set ambitious climate goals that influence its mining practices, including efforts to reduce emissions and adopt greener technologies.
- Innovation in Mining: The country is investing in innovative mining technologies and practices to improve efficiency and minimize environmental impacts.

Government Support

- Incentives for Exploration: Sweden offers various incentives for mineral exploration and development, including funding for projects focused on rare earth elements and critical minerals.

Finland

Legislative Updates

- Mining Act (2011): Finland's Mining Act has been updated to reflect new standards in environmental protection and sustainable mining practices.
- Environmental Permits: The process for obtaining environmental permits has been streamlined to balance efficient resource development with environmental safeguards.
- In 2023, the Finnish government outlined a comprehensive mineral strategy to enhance sustainable production and improve the framework for mineral exploration and production. This strategy is part of a broader set of policies aimed at fostering green industrial development in the coming decades. It emphasizes collaboration with international partners and stakeholders to ensure that Finland remains a key player in the global minerals market. The focus is on balancing economic growth with environmental responsibility, ensuring that Finland's mineral production contributes to both national and European goals for sustainability and strategic autonomy.

Sustainability Initiatives

- Circular Economy: Finland emphasizes a circular economy approach in its mineral sector, focusing on recycling and reusing materials to reduce waste and environmental impact.
- Green Mining: The Finnish government supports projects that incorporate sustainable mining technologies and practices, including those targeting lithium and other critical materials.
- Ongoing exploration efforts are also focused on lithium and precious metals. Supported by Finland’s commitment to sustainability and innovation, these exploration activities are geared towards increasing mineral self-sufficiency. The Finnish government’s objectives include enhancing strategic autonomy and promoting circular economy principles. This forward-thinking approach underscores Finland's dedication to responsible resource management and its role in the global mineral supply chain.

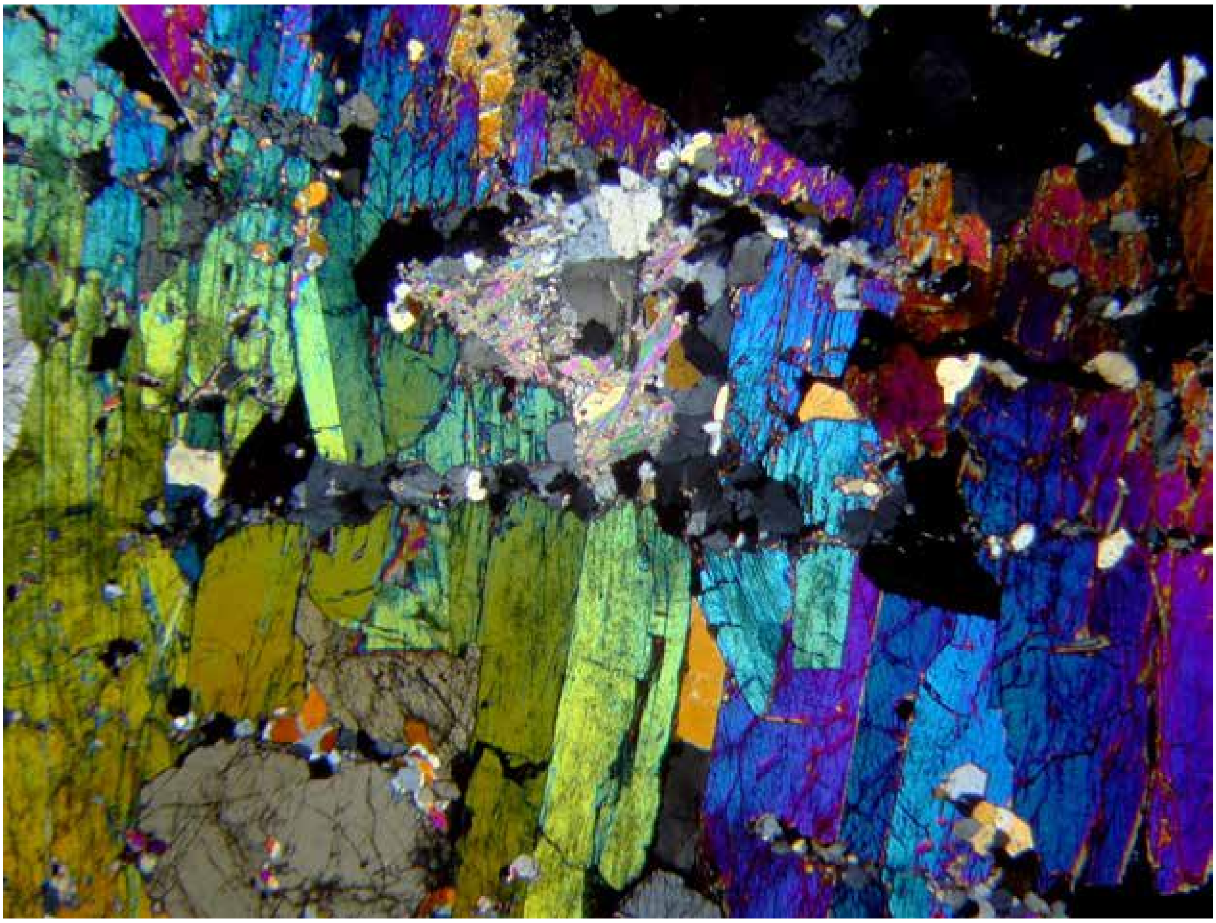
Government Support

- Strategic Initiatives: Finland has strategic initiatives to enhance mineral self-sufficiency and support Europe's strategic autonomy. This includes funding for exploration and innovation in mining technologies.

Summing up the Nordic Country-Specific Strategies

Norway focus on sustainable production, new mineral strategies, and alignment with EU policies. Sweden’s Ambitious climate goals and regulatory enhancements to support green mining and innovation. Finland emphasis on mineral self-sufficiency, circular economy principles, and enhancing Europe’s strategic autonomy.
In summary, the Nordic countries play a pivotal role in the global mineral supply chain. Their combined efforts in sustainable development and technological innovation solidify their position as key suppliers of critical raw materials, essential for a green and technologically advanced future. As such it can substantially contribute to the European raw mateirials supply and Norwegian mining projects a favoured to become Strategic Projects by the EU Critical Raw Materials Act. More than the Nordic countries are enlarging their renewable energy sources which in turn pulls in more downstream investments in the processing of the domestic raw materials as well and in manufacturing.
The Nordic countries, through their rich mineral resources and innovative practices as well as potential of renewable energies and secure energy supply, play a pivotal role in supporting Europe’s transition to a green economy.

GREENPEG Results and Scientific Achievements



Microphotograph of a thin section showing spodumene and lepidolite crystals in crossed polarized light

Helicopter nose boom for mineral exploration in Europe

Claudia Pohl & Klaus Brauch, terratec Geophysical Services GmbH& Co. KG, Heitersheim, Germany

Physical properties of rocks like the electric resistivity, the density and the magnetic susceptibility are used since decades to support the mineral exploration worldwide. These physical properties are measured with airborne, and ground borne geophysical instruments. Their distribution in the underground can be modelled to obtain 3D geophysical models describing the underground. These geophysical models are then translated into geological information to guide the exploration team especially in areas with few outcropping rocks. The main objective of this work is to place expensive boreholes in the right spots also in order to minimize the environmental footprint.

Airborne surveys can cover large areas fast and efficiently and provide data in areas inaccessible to ground-based work. Typically, survey areas for this type of "district scale" measurements are 10 * 20 km large, which is too big for ground and drone borne geophysics. Common platforms carrying the measurement equipment are: 1) fixed-wing aircrafts with magnetometers on tail or wing tip or 2) helicopters with a bird for flat terrain or 3) helicopters with a nose boom magnetometer system for mountainous areas.

The magnetometer measures the magnetic field of the earth and its anomalies. The anomalies are depending on the concentration of magnetic minerals in the rocks. This measurement has a high depth penetration (X*100m) but with a decreasing resolution towards depth. The magnetometer is installed in the nose boom or bird, which usually is a non-magnetic fiberglass housing. Additionally, above mentioned platform types carry inside the cabin a radiometric instrument measuring the U, Th and K content of the upper approximately 30 cm of the ground surface. The combination of magnetic and radiometric measurements in general allows interpretation of lithology and structural geology once the data is visualized on maps. This is done in combination with rock outcrops and literature data used to translate the physical properties into geological information. These maps support the development and improvement of geological models and emplacement histories.

If pegmatites contain abundant magnetic or U, Th and K-bearing minerals and the contrast to the host rock is sufficiently high, a direct identification of pegmatite bodies with airborne surveys allows a high information gain. A ground truth (field measurements) of the anomalies do support the determination of the setting and extension of the pegmatite body raising the accuracy. However, a direct detection of pegmatite bodies is in most cases not possible due to the absence or only low content of magnetic or U, Th or K-bearing minerals in pegmatites. Furthermore, the success of this approach depends on the size of pegmatite bodies. However, what supports this type of exploration for pegmatites is the shape of the pegmatite, which are usually elongated, narrow bodies and often associated with regional linear geological structures, like faults. Hence, such a survey is a basic but efficient method to map lithological contacts and structures controlling features for the presence of pegmatite ore bodies in the early stages of exploration.

However, in order to precisely reveal the pegmatites and these structures, high-resolution surveys with close line spacing of 50 to 80 metres are required. And this is precisely the problem with the use of the first two, above-mentioned carrier systems: For pegmatite exploration in mountainous areas, a helicopter was found to be the ideal platform. For such a high-resolution data acquisition of magnetic and radiometric data both sensors must be as close to the ground as possible. However, this is not possible using the magnetometer bird hanging 30 m below the helicopter. For this bird option a minimum safe flying height of about 70 - 100 metres above ground must be applied depending on topography and vegetation. This is too high for the required resolution in many pegmatite exploration areas.
Our solution is now to connect the magnetometer to the carrier system in a different way to enable the helicopter to fly safely lower. This could be achieved by attaching the magnetometer in a nose boom to the helicopter (Figure 1).
This is already a common procedure outside of Europe, but requires official approval in Europe by the European Union Aviation Safety Agency (EASA) in the form of an so called Supplemental Type Certificate (STC) to be used on European helicopters.

In course of the GREENPEG project terratec could finally operate an EASA certified nose boom and the first demonstration flights could be done to test the whole installation of the boom and the instruments.

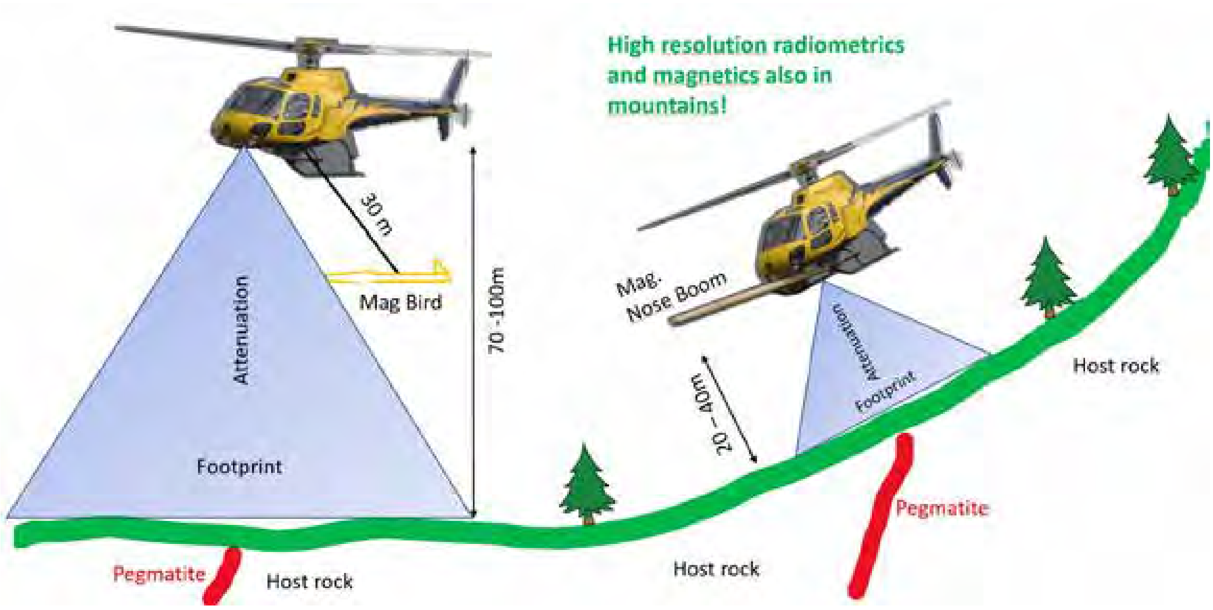


Figure 1: Motivation to use a nose boom for high resolution radiometric and magnetic measurements in mountainous terrain. The magnetometer is installed in the nose boom and the radiometric instrument in the cabin.

Two successful surveys were performed in the summer of 2023. One in the GREENPEG test area at Barroso-Alvão pegmatite field in Portugal, with a total of 640 km flight lines. The other in extreme alpine topography in the Wolfsberg area in Austria with 2347 km flight lines (Figure 2, Figure 3).

Figure 2: Take off of the helicopter with the mounted nose boom from the Wolfsberg airport (photo: terratec).

Figure 3: An impression of the survey flight in Wolfsberg, Austria, co-pilot view. The photo impressively shows the strong topography in the measurement area, which could be flown without any problems using the nose boom on the helicopter

In the following, an example from the Portugal survey explains how such a nose boom data acquisition has been carried out. The survey area in Portugal lies 23 kilometres southwest of the town of Chaves, next to the villages of Adagoi and Bragado. It covers an area of approximately 30 km^2. Airborne surveys are usually performed in a series of parallel traverses and tie lines. The flight plan for Portugal was done first to make sure the area of interest is covered with the line spacing and line directions needed depending on the geological and structural setting of the area of interest and the necessary resolution. This flight plan was then checked by the pilot for obstacles like power lines and for restricted areas like natural reserves and villages. A final version of the flight plan was produced and visualized on Google maps. Fifty metre spaced traverse lines were planned and later flown at low elevation (c.50 m) in a WNW – ESE orientation. An information package was compiled including these maps, photos of a helicopter installation and a general description of the work. This was then used by our Portuguese partners of the University of Porto to inform the local population and authorities providing a phone number as well to be used in case of questions and complaints.
After the information campaign, the survey started from Chaves Aerodrome as a base for take-offs, landings, and refuelling with the helicopter AS350 B3. The team consisted of one pilot and two operators for the instruments. The natural magnetic field must be recorded with a station on the ground to correct the data for daily magnetic field variations and sun wind activities.
Later on, the measured data was processed in the office. As a result, several magnetic and radiometric maps were produced, which could then be used for the interpretation. The interpretation is ideally supported by physical properties measured on rock outcrops and on drill core, to link the measurements to specific rock types and minerals, such as the GREENPEG petrophysical database (Haase & Pohl 2022), see article in this book.

Figure 4 shows a data example of the thorium concentration over the Barosso-Alvão pegmatite field. By using these data sets two different areas could be determined, where the country rocks show different compositions. Additionally, thorium lows marked with circles showed a good correlation with pegmatite rich areas (Ribeiro et al. 2024). This correlation makes it possible to find potentially unknown, buried pegmatites in this area.

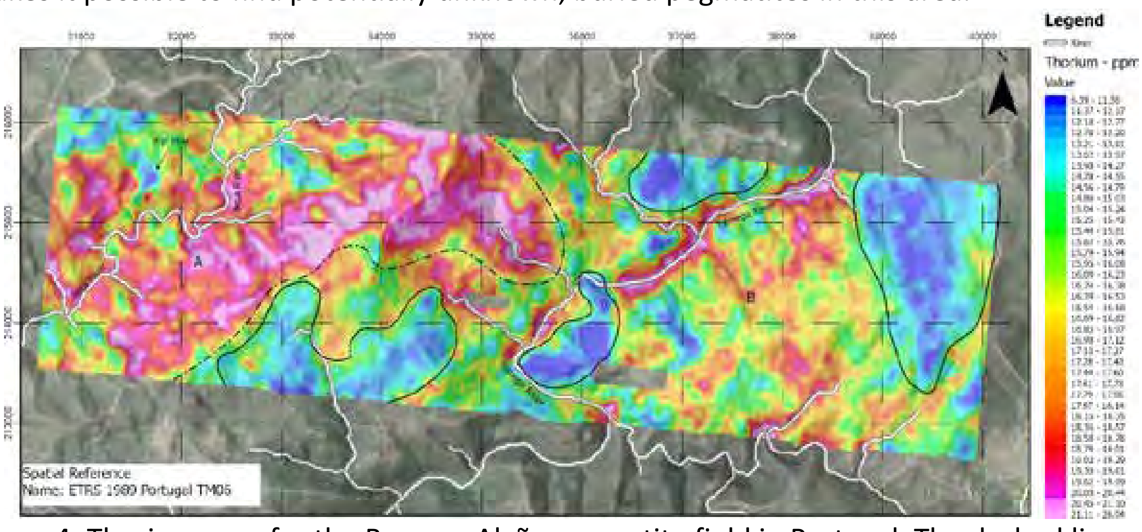


Figure 4: Thorium map for the Barroso-Alvão pegmatite field in Portugal. The dashed line indicates a separation between two areas, where the country rocks have different compositions. The circles represent a possible correlation between low thorium values and pegmatite occurrences.

With this GREENPEG EASA-certificated nose boom magnetometer system, European SMEs will be able to fly lower and more effective airborne surveys. This reduces costs and the environmental footprint of exploration and provides high-resolution magnetic and radiometric data sets.

References

Haase, C., Pohl, C.M. (2022): Petrophysical Database for European Pegmatite Exploration - EuroPeg. Minerals 12: 1498, 16p., https://doi.org/10.3390/min12121498.

Ribeiro, R., Carvalho, A., Lima, A., Moura, R & Brauch, K. (2024): Geophysical exploration in Li Pegmatites from Northern Portugal. GAG-MAC-PEG conference abstract 2024, Brandon, Manitoba, Canada, 4p.

The GREENPEG Piezoelectric seismograph: an innovative contribution to pegmatite exploration

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Motivation

Pegmatite-bound lithium mineralization is currently and in the long term the main solid rock resource for battery-grade lithium. This has already led to an intensive increase in exploration. The exploration for pegmatites is until today a complex and challenging task and mostly applied in areas with known or exposed pegmatite occurrences. Hidden pegmatite deposits, however, are mostly found by accident since exploration tools are limited and often uncertain as they do not retrieve pegmatite-specific petrophysical characteristics. While geophysical methods are widely used in mineral exploration, for pegmatites the classical methods are challenging due to little or missing petrophysical contrast between host rocks and pegmatites. But there is one exception, which is valid for almost all granitic pegmatites. Since most granitic pegmatites contain pegmatitic quartz, one can make use of a special peculiarity of quartz to detect it: the piezoelectric effect of quartz crystals. This effect is the ability to generate an electric charge in response to mechanical stress and vice-versa. We can find its use in everyday applications like spark lighters, acoustic guitars, in Quartz-watches, tire pressure monitoring, just to name a few.

GREENPEG project aimed at finding buried pegmatites in a sustainable and cost-efficient way. Hence, this piezoelectric effect of quartz enables a valuable approach to test and to develop an innovative instrumentation to directly target pegmatitic quartz as an indicator of buried pegmatites. However, the piezoelectric effect is not limited to quartz but occurs for other minerals like e.g. tourmaline and topaz. Nevertheless, quartz crystals have by far the strongest effect and can be easily distinguished from other crystals' piezoelectric response. As a matter of fact, in the Soviet Union comprehensive research had been carried out during the 1950s and 60s on how to apply this effect for mineral exploration with promising results. Based on this experience GREENPEG researchers developed a technologically modern state-of-the-art piezoelectric seismograph and processing tools. Since earlier studies tried to overcome challenges with poor signal-to-noise ration with larger and stronger sources, like larger charges of explosives, we rather tuned the seismograph and the data-processing to varied, small-impact sources in order to construct a pilot which allowed a sustainable and environmentally friendly piezoelectric exploration.

History

The direct piezoelectric effect was first observed by the French crystallographer Gaui in 1817 (Cady, 1946). Later, in 1880, the brothers Pierre and Jacques Curie rediscovered it and studied its manifestations in quartz, tourmaline, and some other minerals (Curie, 1966). By combining their knowledge of piezoelectricity with their understanding of crystal structures and behaviour, the Curie brothers demonstrated the first piezoelectric effect by using crystals of tourmaline, quartz, topaz, cane sugar, and Rochelle salt (Sodium Potassium Tartrate

Tetrahydrate). Their initial demonstration showed that quartz and Rochelle salt exhibited the strongest piezoelectric ability at the time. Up until 1916, when Paul Langevin created the first significant use for piezoelectricity—an ultrasonic underwater detector—it remained a laboratory curiosity.

However, in the 1950s Russian geophysicists studied the piezoelectric effect in detail. Since c. 1964 piezoelectric methods were routinely applied in the Soviet Union to map quarzitic veins in gold exploration (Volarovich & Sobolev, 1965, 1968; Parkhomenko, 1971). Despite its application in the Soviet Union, in the western world piezoelectric seismographs never became a standard method in exploration neither for quartz nor for pegmatites in general. One major issue might have been the often weak piezoelectric signal and consequently a low signal-to-noise ratio, which entailed challenges in data interpretation. The latest attempt to promote this method was by Neishtadt et al. (2006) in a review paper which Eppelbaum (2017) updated in a recent paper, presenting results from successful quartz exploration.

The GREENPEG piezoelectric seismograph

In 2020, NGU started the first tests involving the in-situ measurement of piezoelectric signals in field investigations after a very thorough desktop study of Russian literature about the piezoelectric methodology and analysing the observed challenges and practical issues.
The first test site was a minor quartz vein, about 10 m long and 2 m wide, close to the NGU headquarter in Trondheim. Two electrodes, commonly used for electrical resistivity tomography (ERT) measurements, were connected by 3 m long cables with a battery powered oscilloscope by Hantek DSO8060. As a kinetic source, we used a 5 kg sledgehammer. The NGU researchers used countless attempts and all kind of source-receiver constellations until a clear and reliable first piezoelectric pulse was achieved (Figure 1). The experiment was a success, not only that it confirmed the experiences of the brothers Curie, but also in terms of understanding the major challenges ahead in order to improve the signal-to-noise ratio for uncovering the piezoelectric signal.

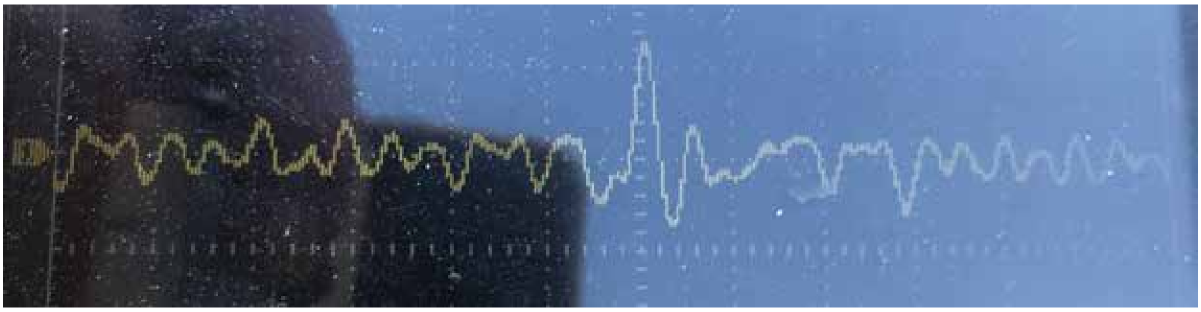

Figure 1: Piezo pulse measured at Ladestien, Trondheim (vertical scale 10 mV, horizontal 5 msec per grid)

From this first test one recognized the piezoelectric signal to be very low, often in the range of a few millivolt and observed a very low signal-to-noise ratio. In our today's technological world electromagnetic signals are omnipresent which is being registered as noise often magnitudes higher than the own piezoelectric signal. As a first step to overcome or at least to reduce this challenge an amplifier was developed, particularly adjusted to EM signals and to unveil the piezoelectric pulse (Figure 2).

Figure 2: A) Specialized amplifier for piezoelectric signals and B) the first prototype for the GREENPEG piezoelectric seismograph.

The NGU team performed numerous tests and trials to determine the various noise sources and their frequency ranges, including noise due to the instrument's architecture and the ambivalent noise of both natural and man-made origin. The results were applied to design and built an amplifier, tailored to subpress this noise and obtain a good signal-to-noise ratio. To ensure its functionality, it was constructed solidly and put through rigorous testing in the lab before further field tests were performed.

At a known partially outcropping quartz deposit in Selbu, close to Trondheim, a second test was conducted, placing electrodes and connecting them to the newly built amplifier and a portable oscilloscope as recording unit. As a source of energy, a 5 kg sledgehammer was used. The second test not only proofed the amplifier is working and that it was possible to increase the signal-to-noise ratio significantly, but it also provided new insights to improve the device further to a real standalone piezoelectric pilot instrument.

In the course of various discussions, the use of modern electronics (microprocessors, MEMS acceleration sensors, AD converters, lithium batteries, GPS modules, etc.) was assessed and a wireless multi-sensor system designed, especially adapted to overcome the experienced challenges with the piezoelectric technology in quartz-rich raw material exploration.

NGU built two units of this prototype, which were deployed and tested in autumn 2020 at the Norwegian GREENPEG test site in Tysfjord, Northern Norway. Different seismic sources like a drop weight and explosives in addition to the sledgehammer were tested (Figure 3). The sledgehammer as well as the drop weight require a hard surface to get the energy transmitted sufficiently into the ground, while for swamp and peat areas explosives are best adapted as well as for soil covered areas.

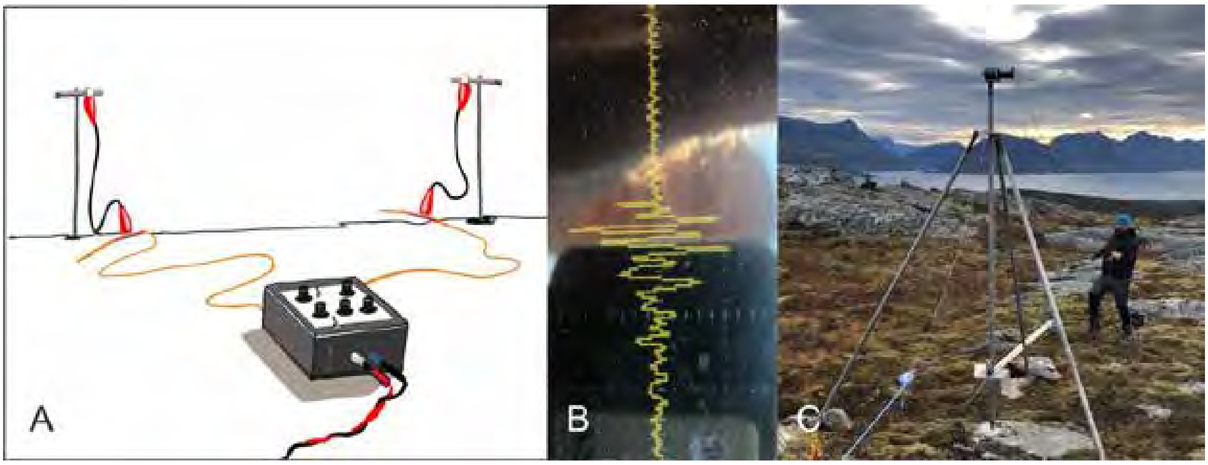

Figure 3: A) Sketch of the measurement setup with 2 electrodes and the amplifier box for the piezoelectric signal (B). C) Drop weight experiment at the test site in Tysfjord.

After numerous measurements, it became obvious that surveying with only two seismographs and one pair of electrodes is little effective. Therefore, a 48 channel ABEM Terraloc Pro seismic equipment was used and updated with a set of 20 amplifiers to adjust the electrode signals to the geophone inputs of the seismograph and amplify the piezoelectric signal sufficiently.

Figure 4: Amplifier box installed at the ABEM Terraloc with up to 48 channels.

During all the tests one learned how to design a survey and place the seismic sources relative to the receivers in an optimal way. Additionally, techniques and software were developed to process and interpret the recorded piezoelectric signal. By the end of 2022 and in summer 2023 NGU carried out the first successful exploration campaigns in connection with the GREENPEG project in Jennyhaugen and Håkonhals open pits at the Tysfjord demonstration site (Figure 5) and in the Koralpe exploration mine of GREENPEG partner European Lithium Ltd. at the Wolfsberg demonstration site in Austria.

In Jennyhaugen the pegmatite mainly consists of feldspar, plagioclase, biotite, and a quartz core with dominant accessory minerals of Niobium, Yttrium and Fluorine. Hence, this pegmatite can be assigned to a NYF type pegmatite. Applying the piezoelectric method, quartz was identified in the hard rock at a depth of 5-10 m which correlated very well with the contrasts shown in other geophysical data. The profile in Håkonhals showed a quartz layer at c. 15-25 m depth, which was confirmed by existing drill cores nearby.

In the Wolfsberg exploration underground mine the pegmatite is exposed in veins. The aim was to identify whether there are more quartz veins in between two tunnels. The piezoelectric response achieved correlated very well with quartz veins which were previously observed in various drill cores. This could be seen as a confirmation that the potential to detect quartz and potential pegmatites with this new instrument is given.

With this now more advanced piezoelectric seismograph the GREENPEG project provides a promising new exploration technique for buried pegmatites. Since this novel method is exclusively sensitive to the presence of quartz, it has a lower ambiguity compared to other geophysical methods applied in pegmatite exploration. More than this it offers an environmental-friendly tool for the exploration and a cost-efficient method for pegmatite exploration, both as a stand-alone method and/or in combination with other methods in brownfield and greenfield exploration.

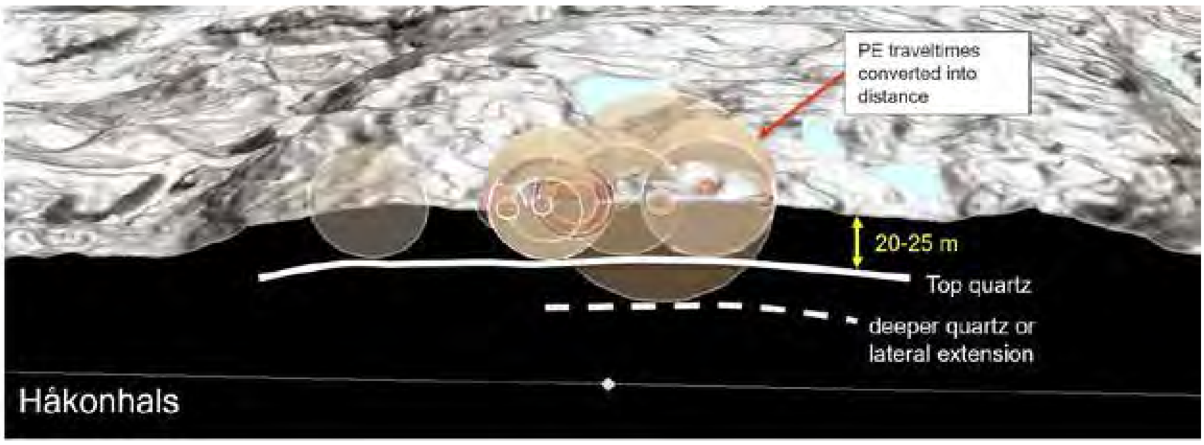

Figure 5: Interpretation of the piezoelectric signals at the Håkonhals demonstration site in Tysfjord.

References

Cady, W.G. (1946) Piezoelectricity. McGraw-Hill, New York and London.

Curie P., 1966, Selected publications: Nauka Publishing (in Russian).

Eppelbaum, L. Quantitative Examination of Piezoelectric/Seismoelectric Anomalies from Near-Surface Targets. *Geosciences* **2017**, *7*, 90. https://doi.org/10.3390/geosciences7030090

Neishtadt, N.M., Eppelbaum, L.V., Levitski, A.G.; Application of piezoelectric and seismoelectrokinetic phenomena in exploration geophysics: Review of Russian and Israeli experiences. *Geophysics* 2006; 71 (2): B41–B53. doi: https://doi.org/10.1190/1.2187714

Parkhomenko E. I., 1971, Electrification phenomena in rocks: Plenum Press.

Volarovich M. P. Parkhomenko E. I. Sobolev G. A., 1965, The way of geophysical prospecting for quartz-bearing veins: Soviet Union Patent 168 812.

Volarovich M. P. Sobolev G. A., 1969, Piezoelectric method of exploration for quartz and pegmatite veins: Nauka Publishers (in Russian).

Drone technology and hyperspectral system

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Background

Exploration business always strives to gain maximum insights on the geological target within an available budget. Depending on the project stage, and therefore exploration scale, the applied methods can reach from satellite data evaluation down to ground geological work and drilling. With the GREENPEG toolset, a guide for choosing a set of promising exploration techniques has been developed. While drone-borne technologies as carrier platforms are already established in a number of civil and professional applications, the application of drones in the exploration of mineral deposits is still not very common.

Drone-borne technology

The development of UAVs (unmanned aerial vehicles, more commonly: drones) has been very rapid in the past years. Drones have been getting smaller, smarter, generally more capable and more versatile. Additionally, drones also dropped heavily in prices and therefore are much more affordable on a small budget.
Common drone-aided technologies, such as aerial imaging and photogrammetry, can also be applied for exploration purposes. If a prospect area has been identified, these techniques help in gaining an initial overview over a number of surface indicators of mineral deposits such as vegetation change and exposure of potential outcrops. Providing a higher resolution than satellite and helicopter and applicable at lower altitudes in undulated terrain they show clear advantage over helicopter-based data acquisition. This starts with the development of high-resolution 3D digital elevation models (DEM) which can help planning future surveys more efficiently.

In addition, drone-borne surveying places itself between ground surveying and aerial surveying by helicopters. With helicopters covering larger areas, UAVs should be considered as an alternative to extensive manual ground work. Data quality and resolution can be adapted to the project's needs by controlling the drone's surveying speed and flying altitude. Multiple ground geophysical methods (magnetics, radiometrics and others) can be employed. UAVs do especially excel in medium-sized areas where employing helicopters is not yet cost-efficient, due to the high impact of transportation and licensing costs, and ground work needs to much time.

But drones are not successfully deployable in every site. Multiple drone-attachable geophysical methods do have a strong distance-resolution-correlation. Therefore, an essential precondition is a low vegetation within the prospect area.
If all preconditions are met, the usage of drone-borne technology allows to retrieve data unreachable by foot with a resolution much higher than satellite and even airborne data.

Hyperspectral imaging

A hyperspectral camera is defined as a camera being capable of detecting the incoming light spectrum as a superposition of light of tightly spaced wavelengths within a specified wavelength range. This differentiates hyperspectral cameras from regular (RGB) cameras, which only capture images as a combination of three colour channels (red, green blue), and multispectral cameras (e.g. NGB), which capture a limited set of non-RGB wavelength (e.g. near-infrared (NIR)).
With light captured as multiple separated wavelengths and the captured images containing pixels in two spatial dimensions (X and Y), captured data can be described as a so-called spectral cube (Figure 1). Depending on the camera type, the data collection process is called spectral scanning (compiling the spectral cube from X-Y-slices) or spatial scanning (compiling the spectral cube from X-wavelength-slices). While this does not make a difference in a lab environment, there is a huge difference in the image acquisition on a UAV. Due to its moving nature, the actually captured object needs to be reconstructed from the collected data. This reconstruction process is far easier with X-Y-slices ("single wavelength images"), since environmental features within the "images" (e.g. objects, trees, rocks) can be used to compensate rotation and distortion.

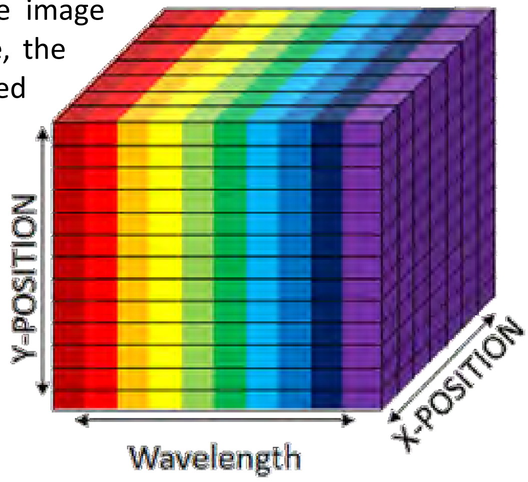

Figure 1: Spectral cube

After the dataset has been acquired, the first processing steps focus on assembling the spectral cube. This includes creating multiple "single wavelength maps" by aligning and stitching the acquired X-Y-slices as it would be done with regular drone-borne imagery.
Hyperspectral imaging has its origins in agricultural monitoring, where the spatial distribution of nutrients (e.g. N, P, K), plant water contents, stress and health are of importance. This is mainly done randomly by attaching a hyperspectral detector on a farming vehicle and acquiring data while doing other tasks, but the usage of UAVs for hyperspectral monitoring is also common.
As agricultural applications are based on chemical properties, this can be transferred over to geological and exploration applications, where geochemical properties are of interest. Rock properties can be gathered from spectral information directly from outcropping rocks, but also indirectly from vegetation above non-outcropping rocks. To extract geochemical information from the hyperspectral data, data classification is necessary. This can be done in multiple ways:

a. Analysing a single wavelength. In the unlikely situation that a single wavelength is sufficient to accurately map a geochemical property, the evaluation of a single-wavelength map will reveal the needed information.
b. Analysing a spectral index. Spectral indices are available for a variety of settings. This available information can be gathered in online databases of scientific publications. Because available spectral indices are specified towards the investigation

target. With the hyperspectral data base of pegmatites deduced from different surface environments by GREENPEG project pegmatite exploration can now be much better supported by using remote sensing. This data base shows high accuracy as GREENPEG project carried out laboratory hyperspectral scans of distinct pegmatite rock specimens at high resolution. However, as hyperspectral imaging is based on the direct interaction of light waves with the target the investigation target needs to be exposed at the surface and must not be covered by vegetation or soil. However, in certain cases geochemical changes of vegetation and/or soil cover due to the interaction with the underlaying mineralisation can reveal indirect information of the hidden investigation target.

Application

Drone-borne hyperspectral imaging (Figure 2) has been successfully deployed at the GREENPEG demonstration site "Tysfjord" in Northern Norway (Figure 4).

Figure 2: Drone-borne acquisition system with equipped hyperspectral camera

While there were no spectral indices available for the surveyed site, hyperspectral data has been analysed by developing a site-specific index, based on pre-existing geological information. A two-wavelength-ratio index (mapped in Figure 3) has been identified to correlate well with the geologically mapped pegmatite outlines (white lines). To allow for a functional data analysis in areas without mapped pegmatite outlines, a preliminary hyperspectral study needs to be conducted on areas with known underlying pegmatite and areas with known underlying host rock to collect information on a potential hyperspectral fingerprint of both geological settings. The preliminary study can potentially be skipped if the setting and hyperspectral fingerprint are already known from comparable sites.

A specialized algorithm has been used to find structures in the acquired dataset. This algorithm scans the spectral map for contrasts (low-value-high-value-border) which are aligned as strings. This helps identifying relevant structures (dotted black lines). The algorithm also allows to ignore certain directions. In the given example, the NW-SE banding originating from vegetative and potentially man-made structures has been ignored.

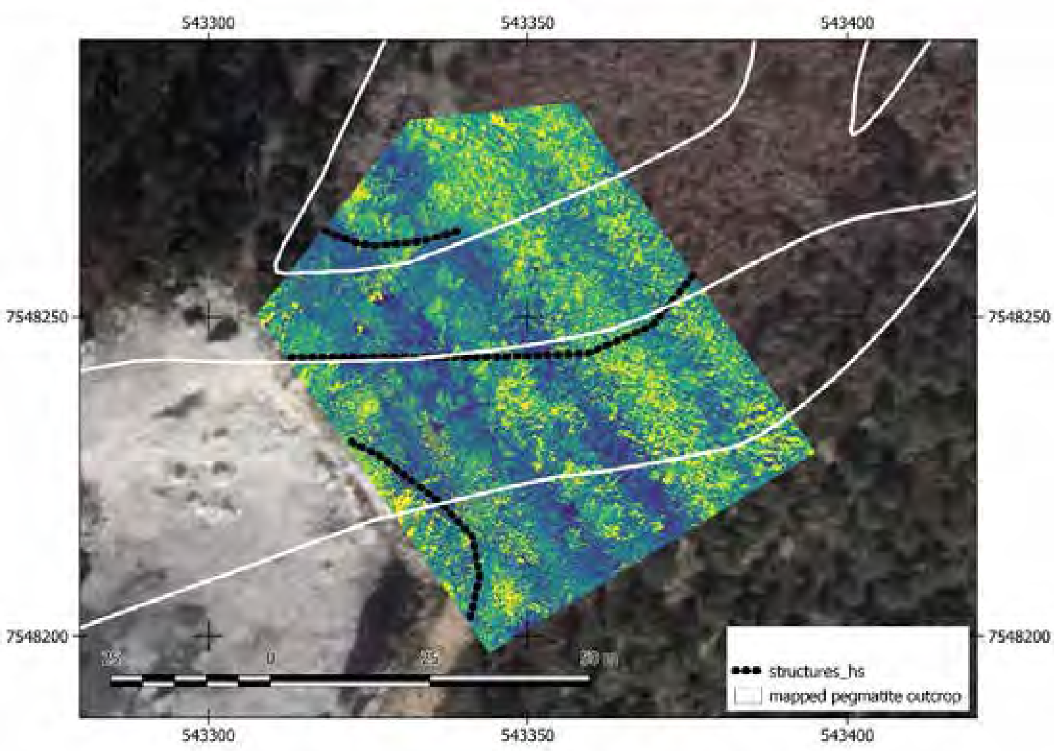

Figure 3: Spectral index (pseudocolored blue (low values) to yellow (high values)) map from drone-borne hyperspectral data acquired at the GREENPEG demonstration site "Tysfjord". Geologically mapped pegmatite outlines (white lines), algorithmically detected structures (dotted black line) and satellite base map. The visible NW-SE-banding is expected to have a man-made origin. To prevent this banding to overlay target structures of geologic origin, the detection algorithm excluded structures in this specific direction.

Figure 4. The surveyed demonstration site "Tysfjord"

Conclusion

The usage of drones in exploration projects is still below its potential. In low-vegetative areas, drone surveying can cover areas unreachable by foot and with higher data resolution than most airborne surveys. This is regularly used for cost-efficient high-resolution aerial imaging, magnetic and radiometric mapping, but also for creating digital elevation models (DEM) using images and LiDAR on small and medium-sized areas. While drone-borne hyperspectral imaging enables UAVs to acquire a type of data completely new to exploration projects, a high gain in information only becomes apparent when reference data (spectral indices of the investigation target) is available. In most situations, a preliminary survey is recommended to acquire suitable reference data.

Petrophysical database and spectral library

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Introduction

Open and accessible data is an important part of the European open data initiative. It allows synergies in research and reproducible results while providing valuable analysis data to industry, academia, and interested individuals. The GREENPEG project contributed with two new datasets to this initiative. The datasets compile different types of measurable characteristics of rocks and/or minerals, providing means to find or distinguish between ore and wall rocks, or mineralised and non-mineralised rocks. By improving the knowledge with respect to these characteristics, exploration strategy and method selection can be optimized in terms of efficiency and success.

Both datasets are open access and accessible through the data repository Zenodo (https://zenodo.org/communities/greenpeg-project). The repository assigns unique Digital Object Identifiers (DOI) and supports a versioning scheme, allowing data updates while keeping the original datasets alive and accessible.

Petrophysical database

Different lithologies can be distinguished by their petrophysical properties. Depending on the rock forming and mineralisation processes, properties may vary significantly or just a little from one lithology to the next. A change in physical properties causes a physical signal that can be recorded by geophysical measurements, but only if the change and hence the signal is large enough. For example, a contrast in densities between two rock units causes a disturbance in the Earth's gravitational field, and a contrast in magnetic susceptibilities causes a disturbance in the Earth's magnetic field. Both effects can be measured with sensitive instruments. Other measurable parameters are for example seismic velocities or electrical conductivity of materials. A solid understanding of physical property contrasts aids in the choice of geophysical exploration methods, and consequently leads to more effective exploration workflows. In the case of exploration for pegmatites, geophysical methods were long neglected or put aside, because the physical property contrast between pegmatites and their wall rocks is often considered too small to cause a measurable signal. On the other hand, a dedicated study on petrophysical properties had not been carried out or published. With GREENPEG, such a data collection was now initiated, allowing quantitative and qualitative investigations.

The petrophysical properties of rocks can be measured on samples in a laboratory, or by geophysical instruments in boreholes measuring in-situ, so-called geophysical wireline logging (Figure 1). For the GREENPEG database, both approaches were used, and the wealth of data was compiled in one comprehensive dataset, the first of its kind dedicated to European pegmatites and their wall rocks (Haase & Pohl, 2022). Sampling for laboratory analysis covered the pegmatite itself, an eventual zoning, and the surrounding host rock (Figure 2). Even though the exploration interest lies mainly with the pegmatite, only by sampling the host rock in addition it is possible to establish the contrast which might give a geophysical signal. The measured data is supplemented with meta-information, such as sample ID, location, sample description, lithology, pegmatite family, photo, and more. This meta-information allows for a range of sorting and filtering options, ideal for statistical analysis of the data and comparative studies.

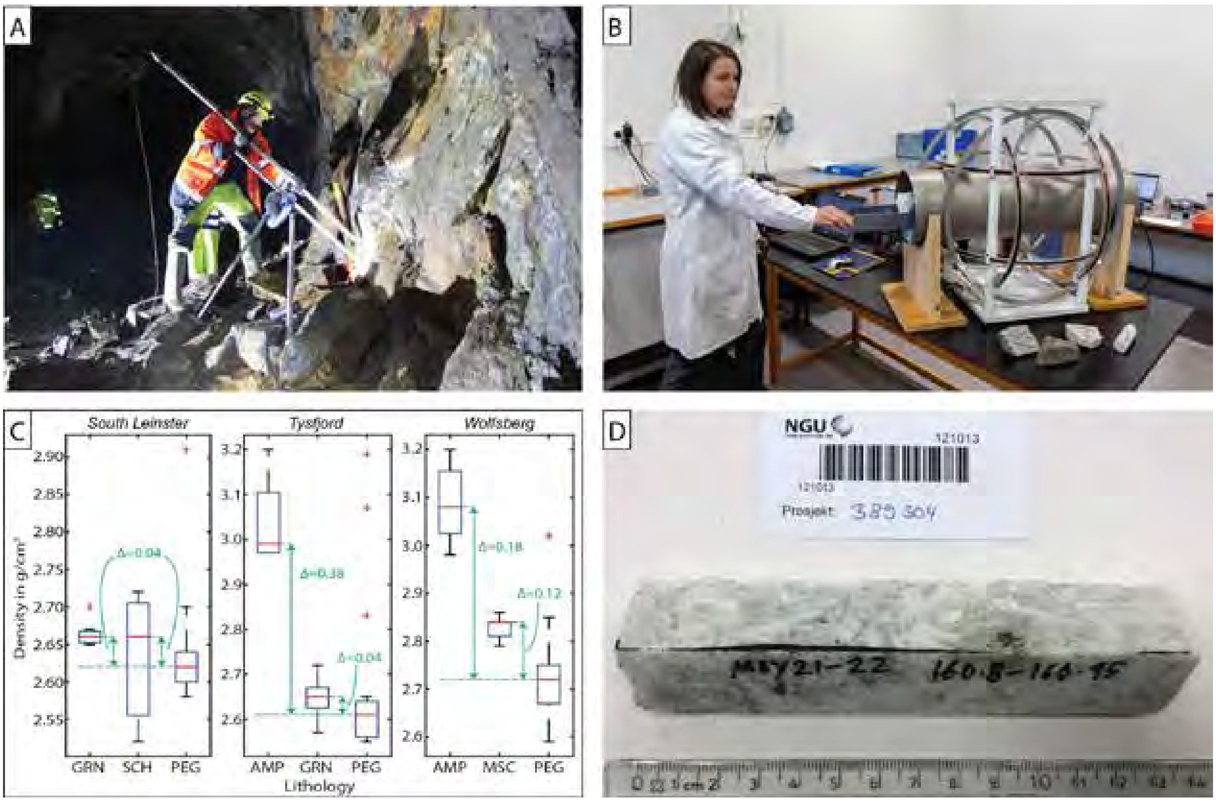

Figure 1: A – Geophysical borehole logging at Koralpe lithium exploration mine, Wolfsberg, Styria, Austria. B – Measurements in the petrophysical laboratory at NGU. C – Results of the density analysis from all three project demonstration sites. It shows that in all cases, pegmatite has a lower density than the host rock. The density contrasts (indicated in green) vary from site to site due to the different geology. D – Sample picture of a drill core sample (quarter core) from the demonstration site in South Leinster. The sample is from an LCT-type pegmatite showing spodumene mineralisation. (Photos: terratec, NGU)

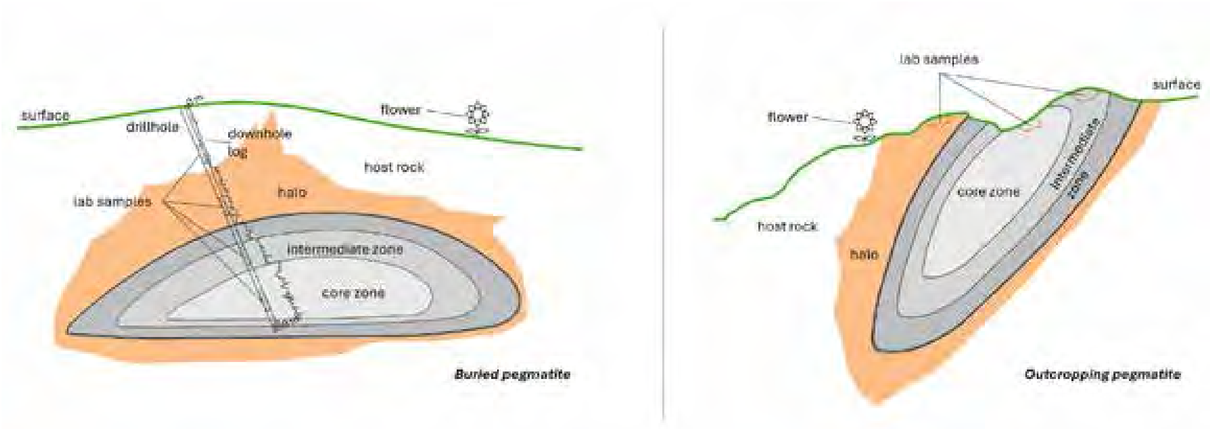

Figure 2: Illustration of one buried and one outcropping pegmatite and their zoning, together with drillhole, wireline logging, and extracted core samples (left) and outcrop samples (right) for petrophysical analysis.

Geographic coverage

So far the dataset comprises project data only, more than 600 entries from 7 locations in Austria, Ireland, Norway, Portugal and Spain. Analyses show that physical properties vary from location to location, even though the same type of pegmatite is investigated. This is due to the varying geological settings and differences in host rocks and pegmatite genesis. Despite these variations, general and site-specific physical contrasts were observed that provide the necessary means for geophysical measurements and aid in data interpretations. This emphasises the importance of petrophysical sample analysis as an integrated part in geophysical exploration. To establish a truly representative dataset over European pegmatites, more data from additional locations will be added to the database over time.

Spectral library

Another of GREENPEG's scientific achievements was its European-wide spectral library, adding new information on the properties of pegmatites and their minerals as well as different host rocks, allowing for the evaluation of the potential of discriminating between the two (pegmatites and host rocks) by remote sensing measuring the reflected sun light at different optical bandwidths.
Reflectance spectroscopy is the study of how light interacts with materials. When light hits a material, some is absorbed, and the rest is reflected (Clark, R. N., 1999). The reflected light forms a spectrum, which is used to determine the material's properties. This technique is crucial for identifying minerals remotely, whether in a laboratory, on the ground, or from space. Optical, multi-, or hyperspectral data allows identifying the types of rocks on Earth's surface by looking at their reflected light. Sensors placed on satellites or UAVs capture the sunlight that bounces off the Earth's surface. Each type of rock-composing mineral or altered rock mineral reflects light in a unique way, creating a kind of "spectral fingerprint" that can be used to classify and map mineralogical / petrographical features. This is possible because the spectrum obtained depends on the material's optical properties and the energy absorbed by the excitation of atoms or molecules in their structure (Bishop, J. L., 2019).

The GREENPEG project has used these advanced techniques to study pegmatites, identifying key minerals and their distributions by examining the spectral signatures of pegmatites (Figure 24). The project has created a spectral library, which is essentially a database of these unique rock fingerprints. This library helps in processing satellite images more effectively. For example, by comparing satellite data (bands) with the spectral library, it is possible to select the best wavelengths for identifying minerals and rocks from space (Figure 3).

Considering the spatial variability of mineral assemblages within the pegmatite samples, their signatures were collected in different spots within rock samples to ensure they capture the full variety of mineral compositions (Cardoso-Fernandes et. Al. 2023), (Figure 24). The same samples analysed for the petrophysical database were measured in the laboratory in a dark room to limit light sources beyond the one specially designed for taking the reflectance measurements (Figure 24). Using known reference spectra from standard databases freely available it was possible to identify the spectral mineralogy in the samples (Kokaly, R. F. et. al. 2017)

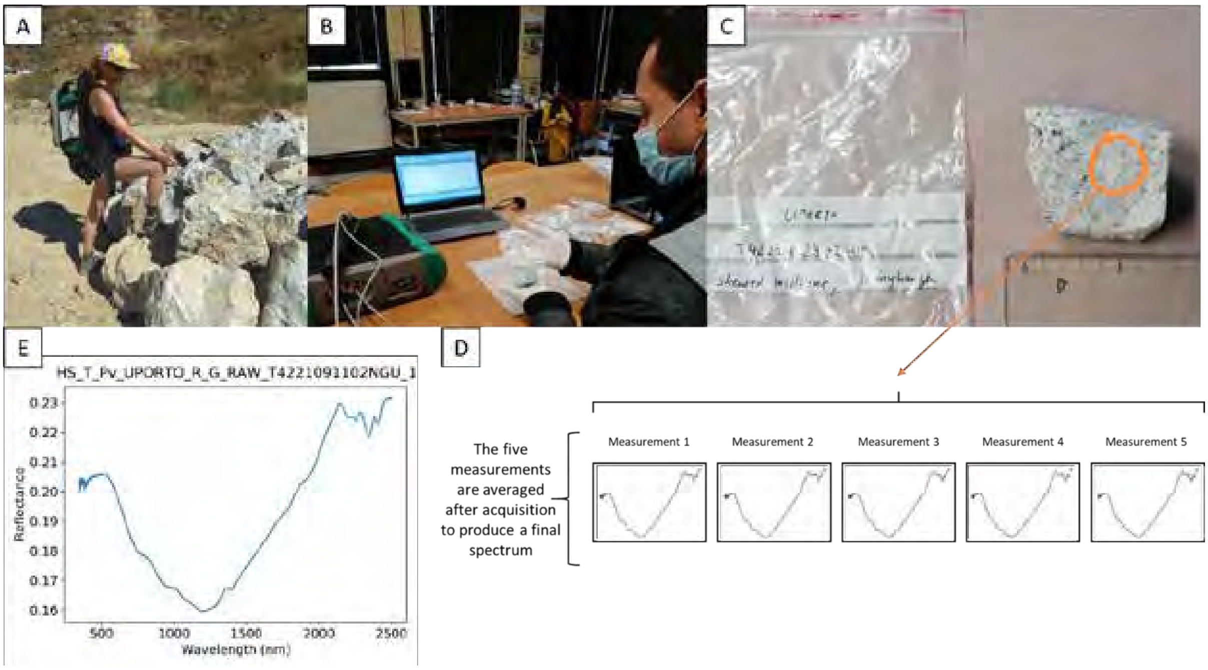

Figure 3: Construction of the spectral library: A – collecting reference spectra of pegmatites in the field; B – collecting reference spectra of pegmatite samples in the laboratory; C – example of the sample photographs available in the database with the indication of where the spectrum was collected (orange circle); D – for each sampling point, five consecutive measurements are collected to increase the signal to noise ratio, which are later averaged into a final spectrum; E – example of the reflectance spectra available in the database.

The GREENPEG project's results show that spectral analysis can sometimes reveal minerals not easily identified by traditional methods like hand samples or microscopy. Insights on how to spectrally discriminate pegmatites from their host rocks were provided. Such information is crucial for users trying to detect other pegmatites worldwide as the spectral library enhances our understanding of pegmatites and their mineral content and has practical implications. For instance, the information can aid in resource estimation and ore processing. It is also a cost-effective measure in the early stages of exploration.

One of the key achievements of the GREENPEG project is making this spectral library compatible with geographic information system (GIS) software (Figure 4). This means researchers worldwide can easily access and use this data for various applications. Using advanced spectral analysis, the GREENPEG project has paved the way for more efficient and accurate geological exploration. This can lead to better resource management and potentially uncover new mineral deposits.

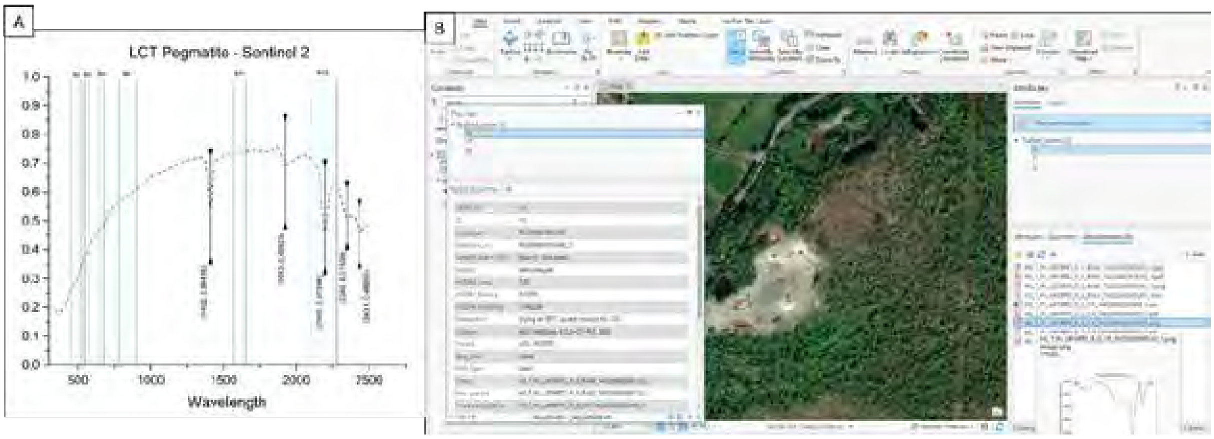

Figure 4: A – Superposition of Sentinel-2 bands over a reference spectrum of an LCT pegmatite. B – An example of the interactive nature of the spectral library provided in GIS-compatible formats; for each sampling point, it is possible to preview all fields in the spectral database and open the attached files.

Conclusions

In summary, the GREENPEG project's petrophysical database and spectral library are significant steps forward in using petrophysical data and remote sensing technology for geological studies and exploration efforts. They offer a wealth of data that can be used to improve our understanding of Earth's pegmatite resources and enhance exploration techniques and workflows, benefiting scientists and industries in gaining more knowledge for less money.

References

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

Clark, R. N. (1999). Spectroscopy of rocks and minerals and principles of spectroscopy: Chapter 1. In R. A. Ryerson (Ed.), Remote Sensing for the Earth Sciences: Manual of Remote Sensing, (3rd ed.). New York, USA: John Wiley & Sons, Inc.

Bishop, J. L. (2019). Visible and Near-Infrared Reflectance Spectroscopy: Laboratory Spectra of Geologic Materials. In J. F. Bell Iii, J. L. Bishop, & J. E. Moersch (Eds.), Remote Compositional Analysis: Techniques for Understanding Spectroscopy, Mineralogy, and Geochemistry of Planetary Surfaces (pp. 68-101). Cambridge: Cambridge University Press.

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 Syst. Sci. Data, 15(7), 3111-3129. doi: 10.5194/essd-15-3111-2023.

Kokaly, R. F., Clark, R. N., Swayze, G. A., Livo, K. E., Hoefen, T. M., Pearson, N. C., Wise, R. A., Benzel, W., Lowers, H. A., Driscoll, R. L., & Klein, A. J. (2017). USGS Spectral Library Version 7 (1035). U. S. G. Survey, Reston, VA. Retrieved from: http://pubs.er.usgs.gov/publication/ds1035

THE GREENPEG Toolbox

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The core result of the GREENPEG project is a new multi-method toolset to explore for buried pegmatites hosting lithium, high purity quartz, and other critical raw materials. This toolset consists of a complementary suite of tailored conventional and newly developed methods, novel data processing approaches, three new geophysical exploration systems and two specialist databases. It is tailored to small and medium scale companies exploring for pegmatites, aiming to maximize the success of subsequent and generally more costly techniques such as drilling. Until very recently, deliberate discovery of buried pegmatites has been almost non-existent, due to an apparent absence of viable detection techniques. This technological-methodological gap has now been addressed by the GREENPEG toolset.

The toolset comprises 26 individual tools/methods (Table 1). The individual tools are optimized for the relatively small size, varying depths, geological settings, physicochemical properties, and different surface environments of pegmatite deposits, from coastal Arctic, to temperate forest, alpine and Mediterranean settings. They are particularly suited to the targeting of lithium, high purity quartz and tantalum deposits. The toolset can be tailored to the geological and broader characteristics and challenges of an exploration area, and to specific customer needs in terms of goals, level of experience and budget.

Scale	**Exploration method**
Province scale (500 - 10,000 km^2)	Spectral identification of outcropping pegmatites
	Morphological identification of pegmatites using LiDAR
	Remote-sensing-supported analysis of regional structures
	Spectral library of pegmatite ores and their wall rocks
District scale (25 - 500 km^2)	Airborne high-resolution magnetics with nose stinger
	Airborne high-resolution radiometry with nose stinger
	Airborne high-resolution electromagnetics
Prospect scale (<25 km^2)	Drone-borne radiometry
	Drone-borne hyperspectrometry
	Electric Resistivity Tomography: Resistivity and Induced Polarization
	Ground magnetics
	Ground spectral radiometry
	Ground penetrating radar
	Ground gravimetry
	Piezoelectric seismograph

	Geological mapping
	Prospect scale structural analysis
	Whole rock geochemical mapping
	LIBS wall rock halo mapping
	Wall rock halo mapping using whole rock chemistry
	Trace-element-in-quartz mapping
	Stream sediment geochemical mapping
	Soil A- and C-horizon geochemical mapping
	Borehole logging
	Petrophysical database of European pegmatite ores and wall rocks
All scales	Environmental, social and governance best practice in exploration

Table 1: List of methodologies of the GREENPEG toolset to explore for buried pegmatites.

Three technological innovations are implemented within the GREENPEG toolset's methodologies: (1) EASA-certified, helicopter-compatible nose stinger magnetometer/radiometer, (2) piezoelectric seismograph, and (3) drone-borne hyperspectral system. In addition, two new databases produced in the GREENPEG project support the exploration methodologies: (1) a spectral library of pegmatites, pegmatite minerals and pegmatite host rocks (Cardoso-Fernandes et al., 2022); accessible on https://doi.org/10.5281/zenodo.6518319) ; and (2) a petrophysical database for pegmatite ores and host rocks (Haase & Pohl, 2022; accessible on https://doi.org/10.5281/zenodo.7347371).

Apart from the technical methods of mineral exploration, GREENPEG has also evaluated the toolset measures in terms of Environment Social Governance (ESG). The accurate application of the toolset, however, will minimize social and environment impacts of the applied exploration activities employing today's ESG standards and in consequence be in line with the objectives of the EU CRMA.

Individual tools were tested mainly in three European pegmatite exploration areas (the so called GREENPEG demonstration sites): Wolfsberg in Austria (alpine), South Leinster in Ireland (temperate forest and farmed land), Tysfjord in Norway (coastal Arctic). In addition, a number of methods were validated in the Central Iberian pegmatite province (Fregeneda-Almendra, Gonçalo, Barroso-Alvão) in Portugal and Spain (hot dry-summer Mediterranean) (Figure 2). To evaluate GREENPEG's geochemical tools in tropical environments, a field survey was conducted in the Alto Ligonha region of the Zambézia province, northeastern Mozambique. Preliminary results suggest that, despite extensive tropical weathering, geochemical ground mapping — particularly the trace-element-in-quartz method — enables the creation of geochemical maps that point to buried pegmatite-related lithium mineralization.


Figure 1: Borehole logging in the Wolfsberg underground exploration mine in Austria by the GREENPEG partner terratec Geophysical Services GmbH.


Figure 2: Sampling and measurement of the host granite to determine the extent and chemical character of the metasomatic halo around a lepidolite-rich pegmatite in the Gonçalo field (Portugal). Photograph: Idoia Garate-Olave.

The toolset will be published in the form of an instructional manuscript comprising five steps: (1) Knowledge development; (2) Desk study; (3) Choice of exploration scale; (4) Choice of exploration methods at respective scale; and (5) Implementation and data integration (Table 2). Step 1 familiarises the users with the physical and chemical characteristics of pegmatites and best practice in environmental, social, and governance (ESG) factors in pegmatite exploration. In step 2, the user can choose which types/genetic classes of pegmatite deposit best fits their exploration scenario. The next step is to decide on the appropriate scale(s) to work at (province, district and/or prospect), which will depend on their objectives, the types and quality of a priori information available and the level of site development (exploration brownfield vs. greenfield). At each scale of exploration, the user can work through a GREENPEG flowchart to decide on the most appropriate methodologies to apply and in which order (Steps 3 and 4). For data integration (Step 5), examples are provided in the appendices of the published toolset. The developed toolset is versatile by offering a range of options, from the design of a complete workflow to individual methods focusing only on special aspects during exploration.

The toolset is designed so that both, experienced exploration companies and regional surveys can apply individual tools or method combinations independently, following the guidance provided in the toolset publication by Müller et al. (2024). Or, if advice or method-performance help is required, the user may contact one of the GREENPEG partners united in the GREENPEG Expert Network, to be contactable under https://greenpeg.eu.

Table 2: Structure of the GREENPEG toolset from Müller et al. (2024).

<table>
<tr><td>Knowledge development</td><td colspan="3">State-of-the-art in pegmatite definition and genetic models, and ESG best practice in exploration</td></tr>
<tr><td>Desk study</td><td colspan="3">Geological environment:
• Understanding of the geological and geographical setting
• Analysis of available datasets
• Application of the mineral systems approach
Exploration environment:
• Analyse the logistical, political, environmental and social environments and requirements
• Develop a community relations strategy
• Combine mappable desk study information using GIS
Financial environment:
• Evaluate financial limitations on which methods can be applied</td></tr>
<tr><td>Choice of exploration scale</td><td>Province scale</td><td>District scale</td><td>Prospect scale</td></tr>
</table>

Choice of exploration methods at respective scale	• Choose method/method combinations • Quantify number and duration of activities for each method • Assess ESG impacts of the methods and regularly review community strategy • Decide order of exploration activities • Perform methods
Implementation and data integration	• As results are obtained, review and revise forthcoming methods • Integrate desk study and exploration results • Review ESG requirements

References

Cardoso-Fernandes, J., Santos, D., Rodrigues de Almeida, C., Lima, A., Teodoro, A.C, GREENPEG Consortium (2022) Spectral library of European pegmatites, pegmatite minerals and pegmatite host-rocks – The GREENPEG project database. Earth System Science Data (https://doi.org/10.5281/zenodo.6518319).

Haase, C., and Pohl, C.M. (2022) Petrophysical Database for European Pegmatite Exploration – EuroPeg. Minerals 12: 1498.

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. Geological Society, London, Special Publications 526: 193-218. https://doi.org/10.1144/SP526-2021-189.

Müller, A., Brönner, M., Menuge, J., Williamson, B., Haase, C., Tassis, G., Pohl, C., Brauch, K., Saalmann, K., Teodoro, A., Roda-Robles, E., Cardoso-Fernandes, J., Smith, K., Wall, F., Lima, A., Santos, D., Hopfner, M., Garate-Olave, I., Errandonea-Martin, J., Harrop, J., Carter, L., Keyser, W., Zhou, H., Nazari-Dehkordi, T., Geiger, E., Unterweissacher, T., Steiner, R., Reimer, W., Pueyo Lloret, C. (2024) The GREENPEG project toolset to explore for buried pegmatites hosting rare metals and high purity quartz. Economic Geology.

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Research and Innovation

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EXPERTS’ NETWORK

Enhance granitic pegmatite exploration – the GREENPEG Toolset

After 4 ½ years, the GREENPEG EU project concluded on 31 October 2024. The major outcome of the GREENPEG EU project is, besides the GREENPEG-developed geophysical exploration devices (EASA-certified, helicopter-compatible nose stinger magnetometer, piezoelectric seismograph, and drone-borne hyperspectral system), a new multi-method toolset to explore for buried, pegmatite-type deposits mineralized in lithium, high-purity quartz, tantalum, tin, ceramic feldspar, beryllium, and caesium. Until very recently, deliberate discovery of buried pegmatites has been almost non-existent, due to an apparent absence of viable detection techniques. The GREENPEG toolset presented is the first to set out a comprehensive guide to exploration for all types of granitic pegmatites. It is based on four years’ work by the GREENPEG team, which has been drawn from 13 academic, industry and government organizations across Europe. The project has allowed mutual exchange of understanding by team members of the wide range of expertise represented in GREENPEG, ranging from remote sensing, geological, and numerous geophysical and geochemical techniques.
Combined with the wide range of methods and technologies developed, adapted and tested, it is this reciprocal understanding of expertise that has led to many new insights into pegmatite exploration methods. One of the strengths of the multidisciplinary consortium was the continuous accumulation of broad knowledge and experience at every project stage and the evaluation and re-assessment of achieved data and applied methods, also of those which have been underrepresented or simply ignored in pegmatite exploration approaches. The result is an exploration toolset equipping small and medium scale companies getting started or progressing in their activities for pegmatite exploration. The toolset will be freely available through an open access publication in the journal Economic Geology by the beginning of 2025.

GREENPEG Experts´Network

Providing advice to stakeholders and services of the method applications, eight GREENPEG partners will continue to work as GREENPEG Expert’s Network, which will commence upon termination of the GREENPEG Project on the 1st of November 2024 ensuring the exploitation and dissemination of the toolset and providing advice if required.

The GREENPEG Expert’s Network aims to

(1) commercialise the knowledge and expertise gained through the GREENPEG project and the technological innovations developed during the GREENPEG project,
(2) provide a comprehensive list and description of the services,
(3) provide information and advertise services through a GREENPEG Expert’s Network webpage, as packages of tools and expertise or individual method offered by each partner or combination of partners, together with their contact information.

Services offered by the GREENPEG Experts' Network are listed in the table below, along with the main knowledge keepers, who are the network members.

Scale	Services: Exploration methods validated	Knowledge keeper(s) (Members of the GREENPEG Experts' Network)
Province scale (500 - 10,000 km^2)	Spectral identification of outcropping pegmatites	University of Porto, c/o Ana Teodoro
	Morphological identification of pegmatites using laser imaging, detection and ranging	University of Porto, c/o Alexandre Lima
	Remote sensing-supported analysis of regional structures	University of Porto, c/o Ana Teodoro
	Spectral library of pegmatite ores and their wall rocks	Online: https://doi.org/10.5281/zenodo.6518319
District scale (25 - 500 km^2)	Airborne high-resolution magnetics performed with nose stinger magnetometer/radiometer	Terratec Geophysical Services GmbH & Co. KG
	Airborne high-resolution radiometry performed with nose stinger magnetometer/radiometer	Terratec Geophysical Services GmbH & Co. KG
	Airborne high-resolution electromagnetics	Terratec Geophysical Services GmbH & Co. KG
Prospect scale (<25 km^2)	Drone-borne radiometry	IFU GmbH Privates Institut für Umweltanalysen
	Drone-borne hyperspectrometry	IFU GmbH Privates Institut für Umweltanalysen
	Electric Resistivity Tomography: Resistivity and Induced Polarization	Terratec Geophysical Services GmbH & Co. KG
	Ground magnetics	Terratec Geophysical Services GmbH & Co. KG
	Ground spectral radiometry	IFU GmbH Privates Institut für Umweltanalysen
	Ground penetrating radar	Geological Survey of Norway, c/o Marco Brönner
	Ground gravimetry	Terratec Geophysical Services GmbH & Co. KG
	Piezoelectric seismography	Geological Survey of Norway, c/o Marco Brönner
	Structural analysis	Geological Survey of Norway, c/o Kerstin Saalmann
	LIBS halo mapping	University of Porto, c/o Alexandre Lima
	Geochemical wall rock halo mapping using whole-rock chemistry	University of Bilbao, c/o Encarnación Roda-Robles

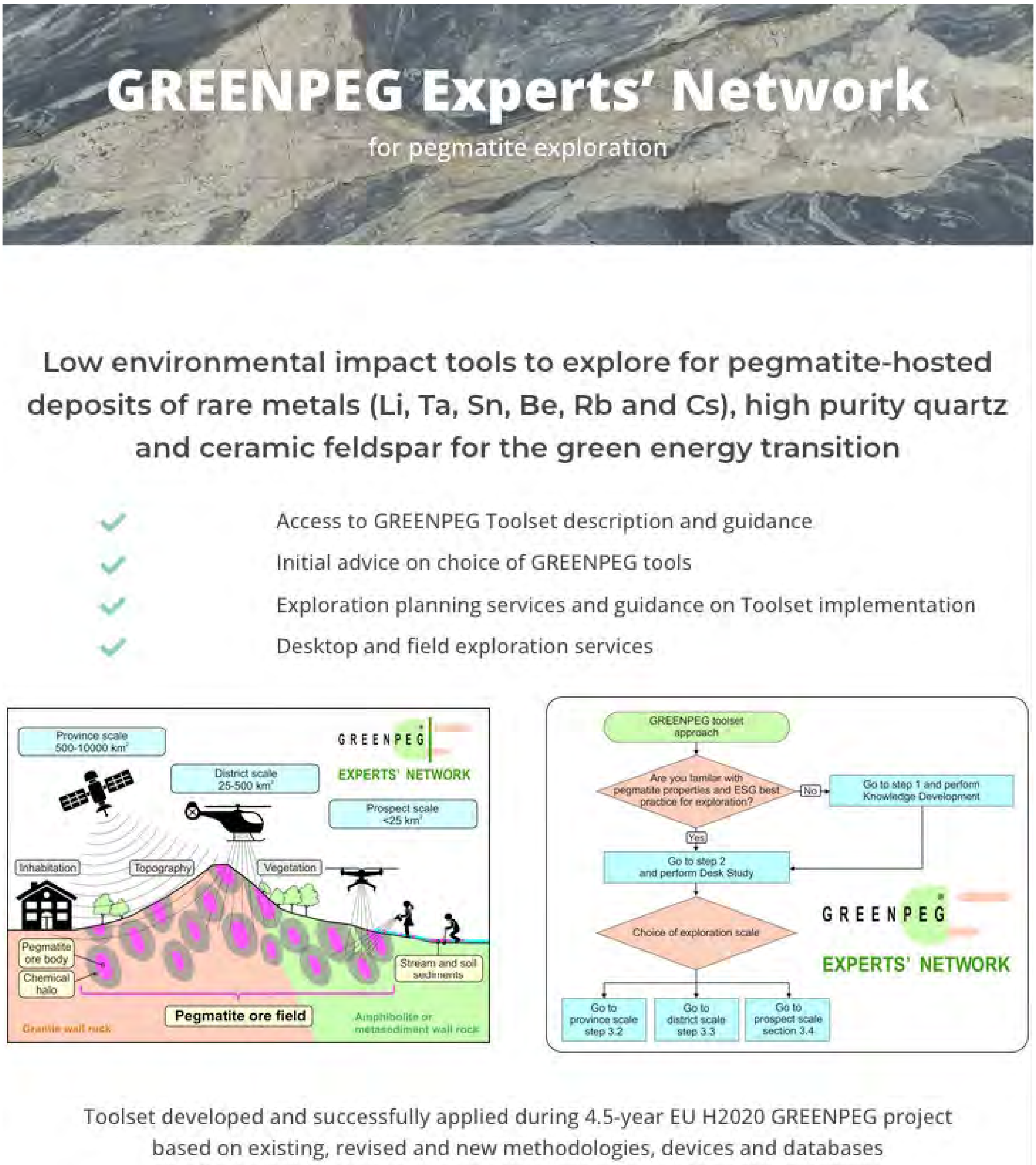
	Trace-elements-in-quartz mapping	University of Oslo, c/o Axel Müller
	Stream sediment geochemical mapping	University of Exeter, c/o Ben Williamson
	Soil A- and C-horizon geochemical mapping	University College of Dublin, c/o Julian Menuge
	Borehole logging	Terratec Geophysical Services GmbH & Co. KG
	Petrophysical database of European pegmatite ores and wall rocks	Online: https://doi.org/10.5281/zenodo.7347371
All scales	Environmental, social and governance best practice in exploration for pegmatites: Services: LCA (Life Cycle Assessment) performance, social impact data collection (online and/or interviews), providing training for people to do best practice ESG	University of Exeter, c/o Kate Smith

Table: Key developed and/or verified exploration tools for pegmatite exploration and the respective knowledge keepers, who are members of the GREENPEG Experts' Network. In green are *the innovations developed by the GREENPEG project, in blue standard methods, but applied or adapted to pegmatites for the first time and in black standard methods which have already been applied and tested successfully on pegmatites.*

The expert initiative is to help companies explore for new pegmatite-related deposits of metals and other commodities needed for green devices such as Li vehicle batteries and magnets for wind turbines, using methods which minimise impacts on the environment and local communities. Success in this will ensure low risk supplies of raw materials to industry and generate employment in the EU and elsewhere through associated commerce.

Contact the GREENPEG Experts´Network

With the termination of the GREENPEG project, the project website www.greenpeg.eu will be transformed into an advisor and service contact platform, launching in January 2025. This platform will offer links to a published exploration toolset, access to specialized databases, and expert consultancy services for pegmatite exploration planning and implementation. Additionally, it will feature new devices developed through the GREENPEG project.



European Technology Platform on Sustainable Mineral Resources

The European Technology Platform on Sustainable Mineral Resources (ETP SMR) is an association of entities operating in the Mineral Resources R&I sector across the whole value chain.

Our mission is to develop long-term European Minerals Industries Research and Innovation agendas and roadmaps for actions at EU and national level.

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- ✓ **Be a part of our ETP SMR Strategic Research and Innovation Agenda (SRIA),** established and driven by our members and defining their common vision of the future challenges, highlighting current needs and gaps. The SRIA serves as an input to the European Commission's research programmes highlighting topics that need to be addressed within the multiannual work programme on raw materials, including calls and partnerships.
- ✓ **Engagement with strategic partners in the raw materials R&I sector**, including close cooperation with exploration and mining companies and other industries from the private sector across the raw materials value chain, as well as the public sector national Geological Surveys of Europe.
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- ✓ **Provide input into the framing of strategic Position Papers on issues of key relevance** to the Raw Materials sector and to the implementation of EU policy and legislation.
- ✓ **Preferential access to an established network of partners for collaboration in raw materials research and innovation projects.**
- ✓ **Become part of a larger community** and **gain visibility on the European stage.**

Find out more on: www.etpsmr.org **Contact us:** info@eurogeosurveys.org

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Imprint

Geokompetenzzentrum Freiberg e.V.
Korngasse 1
D-09599 Freiberg

A publication of GREENPEG - Project
HORIZON 2020 Grant Number 869273

GREENPEG: New Exploration Tools for European Pegmatite Green-Tech Resources - https://www.greenpeg.eu/

Funded by the Horizon 2020 Framework Programme of the European Union GA 869274

Cover photos:
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