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Minerals for future technologies: how Germany copes with challenges

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Abstract: Energy transition, de-carbonization and the future of manufacturing will not end the import dependency of Germany's national economy, but it will most probably result in a shift to new and different dependencies. The need for new raw materials is rapidly increasing. Domestic resources may contribute to but not entirely meet the evolving demand. The supply of new raw materials requires new approaches in exploration supported by sound science. Here, we report in a summarized way on recent results of scientific research projects on critical minerals. Mineral commodities that have important uses and no viable substitutes, yet face potential disruption in supply, are defined as critical to a nation's economic and national security. The main topics are the assessment of critical mineral potential in primary ore deposits and mining waste, exploration of the deep subsurface and thermal brines, bioleaching and deep sea mineral deposits. Raw material development and extraction are affected by environmental concerns, especially groundwater and soil, and societal aspects, such as fair trade in supply chains.

Global population growth, urbanization, increasing standards of living in many developing countries, climate change and the transition to renewable energy supply are among the most important trends of the twenty-first century, accompanied by a continuous need for conflict mitigation and peacekeeping as well as civil society's right to political participation. The production, storage and distribution of energy from renewable sources, further digitization of all economic sectors and new resource-efficient technologies in manufacturing, e.g. lightweight construction, are the drivers of an extreme demand for critical minerals. The term new does not relate to the scientific knowledge or awareness of these minerals. It relates to the knowledge about their geological settings and deposits, the availability of exploration methods, mining and refining technologies, international markets, trade relations and supply chains. Due to the facts that these minerals are subject – for geological reasons – to unequal global distribution and partly occur in geographical areas with unstable socio-economic conditions, the term 'critical minerals' is used. The development of these critical minerals and the consequences of this development for the global economy impact politics and also the political programmes implemented (EU 2020; World Bank 2020).

The German perspective

Germany is an industrialized country with a strong manufacturing industry, representing approximately 25% portion of its gross domestic product. It ranks within the five biggest consuming countries on the global scale in terms of aluminium, copper and zinc. German industry depends on imported raw materials to a remarkable extent. This important dependency will increase with a change in raw materials needed for future technologies. Further, reliable raw material supply chains and a stable energy supply are needed. The national raw materials supply strategy is based on three pillars: domestic resources, recycling and imported raw materials. All three pillars have a special emphasis on the mineral demand for e-mobility, lightweight construction and renewable energy technologies. Strategic cornerstones for domestic mineral supply are responsible sourcing, provision of, and accessibility to geological data, strengthening of the scientific infrastructure, sustainable mine decommissioning, and integration of national and European perspectives. Strategic measures for imported raw materials aim at global monitoring of mineral potential, responsible sourcing, markets and supply chains, fair global trade as well as political support for it.

In 2020 the Federal Parliament of Germany issued the Geological Data Act, which replaced the outdated Repositories Act from 1934. The law obliges the federal and provincial authorities to take up and provide geological data to the public after certain deadlines across the entire Federal Republic. Geological data stemming from commercial studies will also be made public after a specified period of time. The law contains an obligation for the

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responsible authorities to secure geological data so that they are permanently available for the geological tasks of the federal and provincial governments. It also harmonizes obligations to transmit geological data that are important for the production of raw materials and energy as well as for other purposes. The Act also creates an important basis for data transparency.

The Federal Institute for Geosciences and Natural Resources, Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) is Germany's national geological survey and a federal research institute subordinated to the Federal Ministry for Economic Affairs and Climate Protection. Watzel (2019) described its strategic orientation and mission with respect to the challenges that derive from global megatrends. Within the national raw materials strategy BGR is especially engaged in actions for strengthening the scientific infrastructure, assessment of mineral potential, responsible sourcing, and sustainable mine decommissioning, at the national and international level. Embedded within the BGR are the following:

1. the German Mineral Resources Agency (*Deutsche Rohstoffagentur*, DERA) analyses global mineral production and refinery products and evaluates supply risks (Buchholz and Brandenburg 2018);
2. the National Competent Authority of the Regulation EU 2017/821 Conflict Minerals Regulation (EU 2017) (*Deutsche Kontrollstelle für Sorgfaltspflichten in Rohstofflieferketten*, DEKSOR) is responsible for the application of this Regulation and for carrying out ex-post checks in order to ensure that affected companies and other Union importers comply with the mandatory due diligence obligations;
3. the Research and Development Centre for Mining Impacts (*Forschungs- und Entwicklungszentrum Bergbaufolgen*, FEZB) develops new concepts for mining impact mitigation and mine site rehabilitation and has commenced research in the area of lignite mining.

This paper presents the recent outcomes of BGR's research and investigations related to key minerals needed to supply technologies for a sustainable world. On the national level, the focus is on research and appraisal of strategic metals potential, geophysical exploration techniques for the deeper subsurface, the assessment of secondary resources like mine residues and tailings in combination with bioleaching and extraction of lithium from geothermal brines. On the international level, the focus is on the research and appraisal of strategic metals potential, the investigation of marine mineral resources and trading chains. Investigations of sustainability aspects including water risk assessment and environmental impacts related to mining, complement these topics.

Research and appraisal of critical mineral potential

BGR has launched a worldwide investigation of raw material potential of metals of strategic economic importance to safeguard the future supply to the German industry since the 2010s. The main focus of the research topic in a global perspective is on the identification of new raw material potentials of critical metals for high-technology applications. Most of the critical metals, e.g. rare-earth elements (REE), cobalt, scandium, indium and platinum group elements (PGE), generally occur in trace amounts in rocks. They can be enriched in certain rock types and ore minerals, which have formed under specific and complex geological conditions. Consequently, a set of key techniques is beneficial for the development of innovative concepts for exploration for mineral deposits, mining and ore processing. Among them are specialized analytical equipment (e.g. field-emission electron microprobe, time-of-flight ICP mass-spectrometer, micro-energy dispersive X-ray fluorescence spectrometer) and drill core scanning technologies, together with extensive scientific experience especially on the characterization of the distribution of such critical metals in primary and secondary materials. This paper focuses on three scientific key aspects.

Characterization and reassessment of complex non-conventional primary ore deposit types

The knowledge of the specific behaviour of studied critical metals in ore systems is basis for further investigations. The re-evaluation and critical metal-specific characterization of complex non-conventional primary ore deposits are carried out to understand their potential to host critical minerals for energy and technology supply. The research includes a worldwide study of active mines to expand their commodity focus in order to include the recovery of trace metals, as well as the critical metal-specific investigation of new exploration projects. This research topic includes component activities such as: (1) the study of complex ores enriched in heavy REE, yttrium, niobium and tantalum in intrusive and volcanic rocks, e.g. in southern Africa and Morocco (Graupner *et al.* 2015, 2018; Benaouda *et al.* 2020); (2) determining the mineral potential of nickel, cobalt and PGE in magmatites and laterites, e.g. in southern Africa, Indonesia and Brazil (Oberthür *et al.* 2016, 2021); and (3) the investigation and evaluation of rare metal-mineralized magmatic ore bodies, e.g. in Africa and Brazil (Melcher *et al.* 2017). Additionally, a Germany-wide cadastre for historically mined base metal ore bodies has been developed with a special focus on trace element concentrations in ore minerals, e.g. indium, gallium,

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germanium, antimony. Mineralogical and geochemical investigations on 478 samples and ore concentrates from 109 base metal occurrences allow the determination of ore deposit types and geological units with distinct enrichment in one or more of the studied critical metals (Henning *et al.* 2019).

Investigation of critical metal potential of mining waste

The key aim of this research topic is experimental work focused on the optimization of recycling procedures for critical metal-bearing waste by application of automated mineralogy, e.g. scanning electron microscope-based mineral liberation analysis (SEM-MLA). These mineralogical studies were conducted on mine residues with expected critical mineral potential. In this context the conducted research projects are mainly focused on lithium and scandium (Gentzmann *et al.* 2021; Klimpel *et al.* 2021).

Development of new exploration technologies

The research project develops new exploration technologies for complex critical metal-bearing deposits, e.g. drill core scanner methods. Laser-induced breakdown spectroscopy (LIBS) is a promising multi-elemental analysis technology for application in drill core scanners and industrial instrumentation in order to investigate compositional variations in hard rocks and sediments. Its ability to measure light elements as well as its short analysis time make it particular interest. Using a prototype LIBS core scanner at BGR, new LIBS-based approaches for drill core analysis have been developed to: analyse valuable components in tailings (Kuhn *et al.* 2016; Kuhn and Meima 2019); analyse compositional variations such as the magnesium/iron ratio (defined as $[Mg/(Mg + Fe) \times 100]$) in Bushveld ore (Meima and Rammlmair 2020; Meima *et al.* 2022); assess critical parameters for bauxite mining and processing (Meima *et al.* 2021); analyse REE in carbonatite (Müller *et al.* 2021); and analyse lithium-bearing pegmatites (Müller and Meima 2022).

Electromagnetic exploration of the deep subsurface

Over the last several decades there is a clear demand for increased detection depths in the context of raw material exploration programmes. Most near surface mineral resources have been well discovered and evaluated, but their exploitation will not be sufficient to meet growing worldwide demand for minerals. In recent years, there have been advancements in the geophysical instrumentation for mineral exploration using electromagnetic methods.

The development of the ‘Deep Electromagnetic Sounding for Mineral Exploration’ (DESMEX) technologies aims to provide new concepts and geophysical systems for subsurface exploration by combining ground-based and airborne geophysical instrumentation. Airborne electromagnetic methods are well established in mineral exploration because they provide results quickly and inexpensively. Nevertheless, so far airborne-only methods are not suitable for great penetration depths due to their low signal strength. The semi-airborne electromagnetics concept combines the advantages of ground-based electrical dipole transmitters with new developments in airborne receivers (Fig. 1).

As a result of our research, several ground-based transmitter designs and two independent airborne sensing systems towed by a helicopter were developed and successfully tested. In a first step, conventional induction coil systems and fluxgates were used. In a second step, superconductive quantum interference devices (SQUIDS) were applied to measure the subsurface magnetic field responses to the transmitter signals. Trial semi-airborne surveys were successfully performed in the Schleiz region, Germany (Fig. 2), in 2016 (Smirnova *et al.* 2019*a*; Steuer *et al.* 2020). A survey conducted over the Kirunavaara/Luosavaara ore-body in Kiruna, Sweden, in 2018 proved the detection capabilities of the DESMEX system with regard to a narrow (width of *c.* 100 m) and deep (depth of more than 1500 m) ore deposit structure (Smirnova *et al.* 2019*b*). In addition to new data processing, modelling and inversion computing (Rochlitz *et al.* 2019; Becken *et al.* 2020) new strategies for interpreting different aerial geophysical datasets with self-learning algorithms were developed (Cortés-Arroyo *et al.* 2021).

The performance and efficiency of the semi-airborne electromagnetic method will be expanded significantly by further technical innovations. The combined use of ground-based and airborne measurements will be spread from helicopter to drone applications. Another helicopter survey in Scandinavia and the first professional drone applications in Namibia are planned. Furthermore, new SQUID-based magnetometers with a largely increased dynamic range and newly developed highly sensitive optically pumped magnetometers will be applied. The range of new sensing systems includes a new strap-down gravity meter that will be placed into the existing helicopter-towed sensing systems. A major challenge for further development is the attempt to use electrical discharges in the higher atmosphere or stable anthropogenic signals caused by high voltage power lines rather than controlled ground-based sources. Concurrently, a new survey will demonstrate the operational qualities of the technology over the western range of the Harz Mountains, Germany. This project covers all steps from evaluating survey areas, applying the

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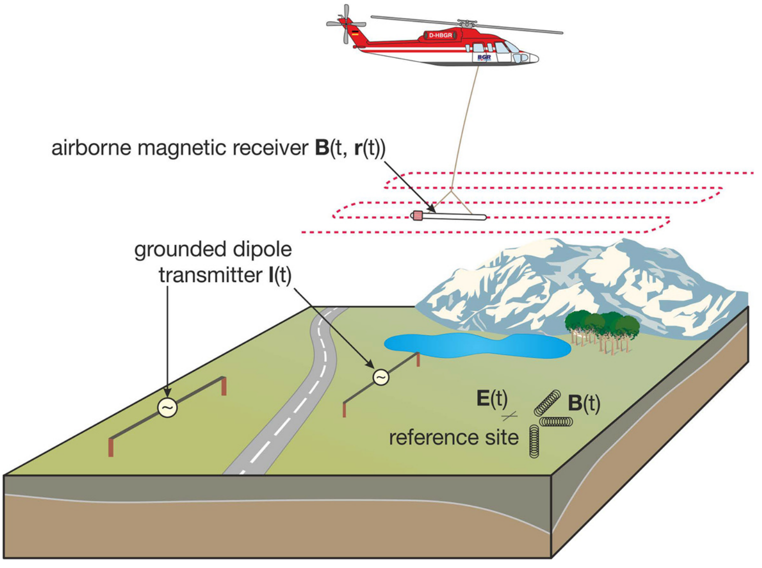

Fig. 1. Semi-airborne EM method with large-scale dipole transmitters **I**(t) on the ground, and airborne receivers towed by a helicopter detecting the magnetic field **B**(t, **r**(t)) where **r**(t) is the location. At a reference site, electric and magnetic fields, **E**(t) and **B**(t), are measured by ground-based receivers (from Steuer *et al.* 2020).

DESMEX technologies, processing, inverting and interpreting the data to recommend areas for further geological exploration. Results will be reported in a timely manner.

Secondary resources in tailings and bioleaching

Exploration and reuse of mining residues

In terms of an efficient and sustainable usage of resources, anthropogenic ore deposits as well as waste accumulations from former production sites become more important for future recovery and reutilization of residual resources. This includes all types of mining residual materials, beneficiation and ore processing. Mining heaps, tailings and slags may contain considerable amounts of valuable components, as well as precious and trace metals that are of significant need for high technology applications. Reprocessing of mining residues is ideally combined with an environmentally friendlier re-deposition of processed heaps, or with a comprehensive usage of all materials.

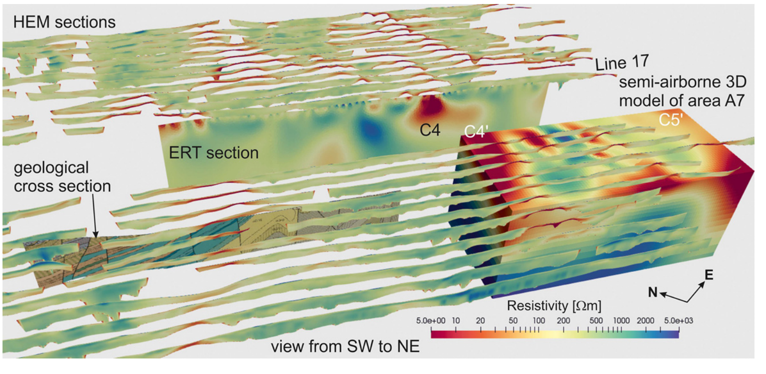

Fig. 2. Perspective view of a part of frequency-domain helicopter-borne EM sections together with the semi-airborne EM 3D inversion model of sub-area A7 on the right side and the ERT section in between. Discussed conductive anomalies are indexed with C. A geological cross-section with the submerged layers of the Silurian alum shales (turquoise colour) is also shown (from Steuer *et al.* 2020).

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BGR's research aims to identify and characterize the resource potential in mining residues, as well as further develop methods for investigation and assessment of mining residues. Dumps consisting of mining residues are far from homogeneous. Any changes in the origin of the primary ore, in ore treatment processes, or in the way a dump is shaped, may affect spatial geochemical, mineralogical and textural material properties of a dump. Additionally, geochemical and physical processes during and after deposition may produce distinct areas of metal enrichment. The described spatial variations are relevant for efficient re-processing and minimization of mass transport, and, consequently, for assessing possible economic recovery opportunities.

BGR focuses on the development and application of interdisciplinary exploration methods to assess compositional variations for base and precious metals on different scales (Nikonow *et al.* 2019). In the field, the importance of drilling and geophysical methods has been recognized, because material properties at the top of a dump are seldom representative for material properties inside the dump. In the laboratory, the importance of a combination of fast scanning methods, such as hyperspectral imaging (HSI), LIBS and energy dispersive X-ray fluorescence (EDXRF) with bulk chemical analysis and micro analysis (micro energy dispersive X-ray fluorescence (μ-EDXRF), SEM-MLA, Raman spectroscopy, electron microprobe) has been recognized (Kuhn *et al.* 2016; Berkh *et al.* 2019; Nikonow and Rammlmair 2019). Whilst micro analytical methods help to identify target element mineral properties as needed for selecting appropriate processing technologies, fast scanning methods help to identify changes in mineralogy, geochemistry and texture as well as regions of enrichment of specific target metals.

A Germany-wide cadastre with over 2000 metalliferous mining dumps has been developed in close co-operation with German partner research institutions (*ROBEHA* project 2012–21; http://www.robeha.de). Germany has a long mining tradition, and this is reflected by a large number of small- to medium-sized mining dumps. However, chemical and mineralogical data are only available for specific case studies. BGR has participated in a number of such case studies, mainly focusing on base metals and the precious metals associated with them. For example, the metal content of a historical tailings site from gravity separation was estimated to contain 8000 t of lead and 18 t of silver (Kuhn and Meima 2019). Although of limited economic value, recycling might finance future remediation costs. Reprocessing of mining residues in Germany is faced by a number of challenges. Among these are the generally small size of most of the dumps and the missing chemical and mineralogical information; further, current land use and ownership structures contribute to the challenges

Bioleaching

Biohydrometallurgy as a subfield of hydrometallurgy takes advantage of specialized, harmless acidophilic bacteria for ore processing (Komnitsas 2019). These acidophilic bacteria (e.g. *Acidithiobacillus ferrooxidans*) are able to dissolve sulfide minerals in ores, and this phenomenon is applied as biomining, e.g. for copper recovery from low-grade ores in large-scale bioheap-leaching operations mainly in Chile (Figs 3 & 4). The distribution of acidophilic microorganisms in natural and anthropogenic acidic environments has recently been reviewed (Hedrich and Schippers 2021).

Recent advances in mineral ore processing via biohydrometallurgy in BGR have comprised platinum group element (PGE) ores, copper ores and laterite ores, as well as ore processing residues (mine tailings). PGEs are used for many high

Fig. 3. Tailings dam of the Las Luces copper mine, Taltal Region, Chile.

Fig. 4. Heap bioleaching for copper recovery in Quebreda Blanca, Chile.

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technology applications, and the world's largest PGE deposit is the Bushveld Complex in South Africa. Near-surface oxidized PGE ore is currently stockpiled there since an economic extraction of PGE from these stockpiles using conventional technologies is not feasible to date. Following a new strategy by combining bioleaching with chemical extraction resulted in up to 89% platinum and 96% palladium extraction from the ore (Hedrich *et al.* 2020). The most abundant copper-bearing mineral in copper ores worldwide is chalcopyrite; however, its dissolution in leaching processes is challenging. The addition of pyrite to chalcopyrite-rich ores led to enhanced chalcopyrite dissolution in bioleaching laboratory experiments, and this finding has been verified by electrochemical analyses (Tanne and Schippers 2021). Another successful new strategy was to apply a distinct temperature regime in the tank bioleaching process, which led to an almost complete dissolution of chalcopyrite and maximal copper recovery (Hedrich *et al.* 2018). Laterites are the main ore deposit type for nickel with a high potential for cobalt as well. The novel approach of reductive bioleaching (in contrast to the established oxidative bioleaching of low-grade sulfide ores) led to a high degree of extraction of nickel and cobalt from limonitic laterite ores in laboratory experiments; such ores are currently commonly stored as stockpiles in laterite mines worldwide (Marrero *et al.* 2015, 2020). Process development, optimization and evaluation is currently being conducted in BGR in collaboration with partners in Germany and Brazil. Mine tailings commonly contain significant amounts of valuable metals; however, their extraction requires a complex technology and this may not be economically feasible. Bioleaching as a rather low-cost processing technology has been successfully tested for metal extraction in the laboratory (Fig. 5). Bioleaching of tailings from the former Rammelsberg mine (Harz Mountains, Germany) resulted in 91% cobalt and 57% copper extraction from the bulk tailings (Zhang *et al.* 2020) as well as in the discovery of a novel bacterial species (Zhang *et al.* 2021).

Fig. 5. Bioleaching for metal recovery in stirred reactors in the BGR geomicrobiology laboratory.

Lithium from geothermal brines

The German Mineral Resources Agency (DERA) expects the global demand for lithium to double or even triple by 2025 (Schmidt 2017). A more detailed study expects the German demand for lithium to increase from 7500 t in 2018 to a range between 85 000 and 558 000 t in 2040 (Marscheider-Weidemann *et al.* 2021). The use of lithium in rechargeable batteries, especially in electric mobility, has been identified as a major driver for this development (Buchholz and Brandenburg 2018). Worldwide, lithium is sourced mostly from South America and Australia currently. In addition to the traditional methods of lithium production from the South American salars and Australian pegmatite deposits, additional sources are currently being evaluated worldwide.

According to our conservative estimations, the lithium resources in sedimentary formation waters with lithium concentrations above 100 mg l^{-1} are known in geothermal brines from depths down to 5000 m. Fluids from some sedimentary reservoirs (Sanjuan *et al.* 2022 and references within) are characterized by high lithium concentrations similar to those from salars (Steinmetz and Salvi 2021 and references within). Such fluids are brines with salinities ten times greater than seawater (Riley and Tongudai 1964). The available resources within such fluids calculated using conservative assumptions show that they are comparable to currently-exploited salars and hard-rock mines (Dugamin *et al.* 2021). In Germany lithium contents of up to 350 mg l^{-1} are measured in geothermal brines in the North German Basin (Kloppmann *et al.* 2001; Lüders *et al.* 2010) and up to 200 mg l^{-1} in the Upper Rhine Graben (Sanjuan *et al.* 2016; Dugamin *et al.* 2021) (Fig. 6).

BGR launched the *Li⁺Fluids* project in October 2021. It aims at evaluating the technical, geological and economic basis for a future lithium extraction from fluids at geothermal sites in Germany. In order to be able to make economically sound statements on hydrothermal fluids as lithium deposits, the origin, distribution and, above all, the subsequent deliverability of lithium is subject to investigation and evaluation in detail. Therefore, the project's investigations focus on the 'geological sustainability' of lithium extraction from deep fluids. The basic idea is to deplete lithium in the circular flux of a geothermal facility. The re-injected fluid, depleted in lithium, has to be re-enriched by fluid–rock interaction within the geothermal circulation loop. The re-enrichment of lithium from the adjacent rock formations is crucial for the long-term viability and

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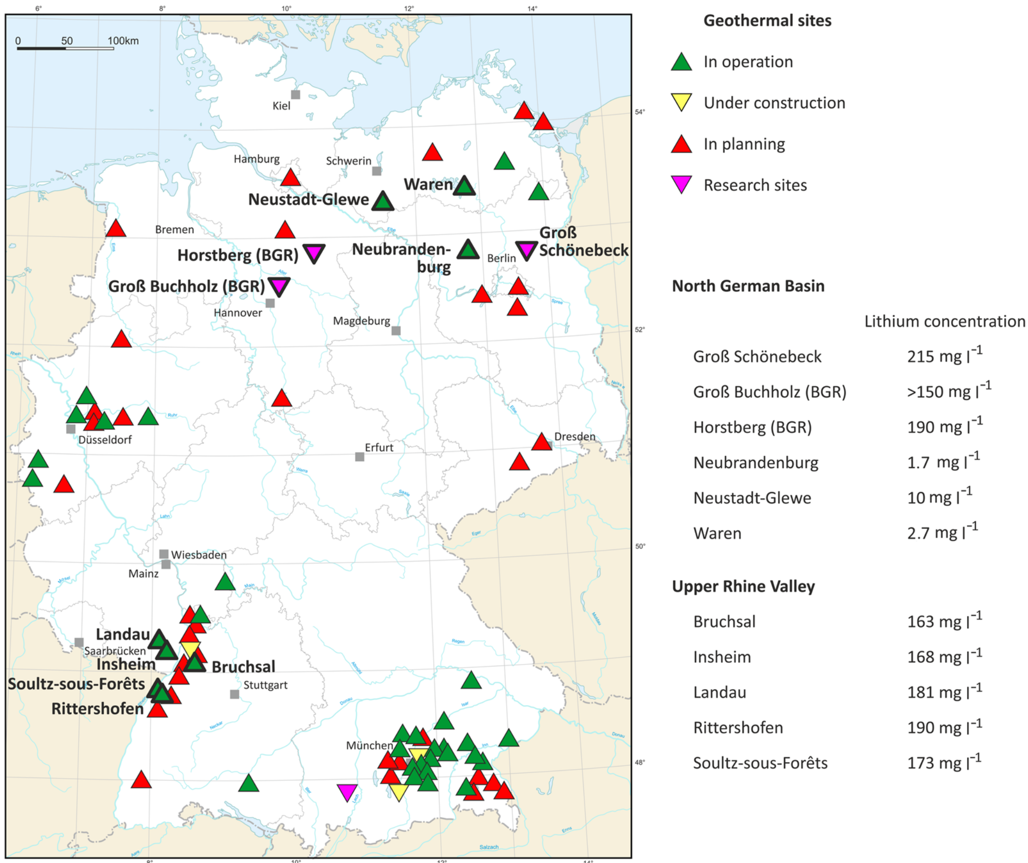

Fig. 6. Lithium concentrations in selected geothermal sites in Germany and the French part of the Upper Rhine Graben; data from Geothermal Information System GeotIS (http://www.geotis.de) (Agemar *et al.* 2014*a*, *b*) and from Sanjuan *et al.* 2016.

economic feasibility. To estimate the delivery of lithium from the geothermal reservoir in a circulatory operation, time-resolved experimental series are being carried out for rock material of the North German Basin and the Upper Rhine Graben. Basic time-scales and physicochemical mechanisms of lithium exchange reactions and solution processes between rock and fluid are being systematically investigated by means of laboratory experiments. High-pressure reactors simulate the pressure and temperature conditions of the respective geological reservoir to determine lithium release rates. The focus is on understanding and quantifying the influence of temperature, fluid chemistry (especially salinity and concentration of dissolved CO_2) and the available reactive surfaces on solution equilibria and reaction rates. In addition, drill core flow experiments are being carried out on selected drill core material.

Investigation of marine mineral resources

BGR's marine resource exploration covers polymetallic (manganese) nodules and massive sulfides. On behalf of the German government the institute holds two exploration licences issued by the International Seabed Authority (ISA): one licence for manganese nodules in the Equatorial Northeastern Pacific (since 2006) and one licence for massive sulfides in the western Indian Ocean (since 2015). Manganese nodules contain economically relevant metals like copper, nickel and cobalt, which together make up to 3 wt% of the nodules (Kuhn and Rühlemann 2021). Seafloor polymetallic sulfides contain high abundances of base metals (copper, lead and zinc), precious metals (gold and silver) and high-technology metals (indium, germanium, bismuth and selenium). One aspect of BGR's investigations focus is the processing of seabed mineralization to

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evaluating the economic feasibility of mining (Sommerfeld *et al.* 2018, 2019; Wegorzewski *et al.* 2018).

The majority of the institute's investigations are focused on the environmental impact of future seabed mining (Gillard *et al.* 2019; Janssen *et al.* 2019; Kuhn *et al.* 2020; Uhlenkott *et al.* 2020). Studies on benthic habitats, deep sea fauna, biogeography and abyssal sediment plumes, comprised 50% of the research spending. BGR participated in the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Oceans) research project *MiningImpact* in 2021. JPI Oceans is a pan-European intergovernmental platform that increases the efficiency and impact of research and innovation for sustainably healthy and productive seas and oceans. The project aimed at assessing the environmental impact of a manganese nodule collection test. The test was carried out in the manganese nodule belt in the Pacific Ocean between Hawaii and Mexico. The nodules were collected by a Belgian enterprise within the Belgian and German licence areas. The collecting device operated from a ship operated at a depth of *c.* 4000 m below sea level. Concomitantly, 29 international scientists on board a second ship participated in the scientific monitoring of the environmental impact. Two Remote Operated Vehicles (ROV), Autonomous Underwater Vehicles (AUV) as well as *in situ* sensors for oxygen, hydro-acoustic and optics for the determination and characterization of the sediment plume were deployed during the test. The data are currently being evaluated and readied for publication. The results of the mining impact test will contribute to the regulation of environmental standards by the ISA.

Environmental and societal aspects

Water risk assessment, environmental impacts and trading chains

The national raw materials strategy comprises strategic issues with respect to imported materials. The most important aspects that touch BGR's mandate as federal institute and geological survey organization are responsible sourcing and fair supply chains. Mining causes environmental impacts. It is a challenge and a duty to minimize them, to end up in best practices for sustaining the globe. Gilsbach *et al.* (2019) focus on water risk assessment methods in mining. Langkau and Erdmann (2021) research environmental impacts of rare earth mining for magnet applications in a global scope.

Mining of critical minerals in Africa focuses on several societal concerns, especially in the sector of artisanal and small-scale mining, and these are covered by National and EU regulations. BGR holds the National Competent Authority of EU's Conflict Minerals Regulation and legal duties. It is supported by the institute's investigations on mining conditions, international mineral trade and sustainability and responsibility issues (Schütte 2019; Franken *et al.* 2020; Schütte and Näher 2020; Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) 2021).

In this context BGR has established the Analytical Fingerprint (AFP) method since 2006 as a contribution to calls by the UN for a scheme to verify the origin of 'conflict minerals' mined in the eastern Democratic Republic of the Congo and neighbouring countries. The AFP method is a scientific tool which can be used to verify the documented origin of tin, tungsten, and tantalum (3 T) ore mineral shipments. AFP compares a sample from a shipment in question to reference samples of the documented origin stored in a database. As such AFP combines the identification of characteristic geochemical features preserved in mineral concentrates and applied statistics (Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) 2018). As a result, the AFP evaluates whether the origin given in the documents of a shipment in question is plausible or not. The AFP is not intended to be applied as a stand-alone method for mineral sourcing decisions, nor is it intended to be applied as a regular tool to control every mineral shipment. Likewise, the AFP does not represent an alternative to everyday mineral traceability techniques (e.g. tagging) but serves to verify the integrity, and thus credibility, of the latter. As part of technical cooperation efforts within the regional German support programme running from 2011–22, BGR aims to make the AFP method available to the International Conference on the Great Lakes Region (ICGLR) and partners, including a transfer of skills, technology, and management into the region.

Conclusions

Germany's primary energy supply and raw material supply for the manufacturing industry has been highly dependent on imports for many decades. With regard to the energy transition and decarbonization, dependency on imported fossil fuels will decrease in the future, but dependency on minerals for future technologies, both in terms of energy supply and manufacturing, will continue. The national raw materials supply strategy, based on domestic resources, recycling and imported raw materials is strongly supported by the BGR. The BGR's research is focused on technologies for deposit exploration in deep parts of the subsurface together with thermal brines as a source of lithium, and the reuse of secondary materials. It is not yet proven

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whether the domestic mineral repositories in mining waste and lithium-enriched brines may be processed in an economically feasible way. With regard to imported critical minerals, an ongoing reassessment of complex non-conventional primary ore deposit types delivered first results. The research will continue. These findings support Germany's decision-making processes in its foreign economic affairs. BGR's activities with regard to recycling commenced in 2021 and first results will be reported in the near future. The results achieved to date in exploring deep sea mineral deposits in the German licence areas deliver a clear picture of metal potential in manganese nodules and massive sulfides. Major challenges for future mining opportunities derive from suitable mining technology and environmental impact assessment. One of the main considerations in deep sea mining opportunities is potential environmental impact. For this reason, Germany spends the same amount of resources for environmental impact analysis as for deposit exploration in order to support the International Seabed Authority in establishing mining regulations. As Germany's foreign policy is strongly committed to responsible sourcing principles and fair international supply chains, environmental and societal issues are part of the mineral research portfolio. Increasingly, countries are becoming aware of the importance of what is called the social licence to operate. Thus, our activities aim at a holistic scientific picture of raw material sourcing. Sound scientific investigations and assessments are crucial for sustainable decision making.

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