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Proceeding Paper

Critical Raw Material Resource Potentials in Europe †

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Abstract: The vulnerability of economies and the associated familiar lifestyles have led to numerous policy measures in Europe. The proposed Critical Raw Materials Act (CRMA) sets indicative targets for 2030. A sustainable change in the supply situation requires the targeted exploration of raw materials precisely within the framework of national geological research of suitable detail and in advance of entrepreneurial raw material projects. EU projects like GeoERA assist in shaping the tailor-made exploration programs fit for purpose. GeoERA scientific projects like FRAME and MINDeSEA completed, and updated existing mineral data on CRM are publicly available through EuroGeoSurveys' European Geological Data Infrastructure (EGDI).

Keywords: critical raw materials; exploration; mineral; Europe; Critical Raw Materials Act

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1. Introduction

Raw materials have been the backbone of human civilization since prehistoric times. Entire epochs have been named after them, namely the Stone Age, the Copper Age (Chalcolithic), the Bronze Age and the Iron Age. Knowledge of their occurrence, and responsible and sustainable methods to extract and process the various raw materials are crucial insights linked to societal prosperity and well-being. From ancient to modern times, this commodity-driven prosperity can be observed in many places in Europe and elsewhere. The Greek region of Laurion, south of Athens, is just one of them.

Still, raw materials are essential resources used in the production of various goods and technologies, ranging from daily consumer goods, electronics and renewable energy systems to pharmaceuticals and transportation. They all have a fundamental, everyday impact on the population. Due to their economic importance, limited availability or high risk of supply disruption, several minerals play crucial roles in supporting key industries and enabling technological advancements and hence are labeled "critical" and "strategic" raw materials.

The current geopolitical situation has refocused attention on raw materials issues again. The recent and current crises, the financial crises of 2008, the pandemic of 2019 to 2021, high inflation rates in Europe since 2022, global climate change and the war in the Ukraine, to name but a few, have brought the crucial importance of commodities to our lives back to the fore. In many places, including in the EU, measures are being taken to sustainably secure the supply of raw materials in line with the UN sustainability criteria, thus promoting ecological development and technological progress. Addressing the challenges related to critical raw materials requires a comprehensive approach involving policy coordination, international cooperation, research and development, and sustainable practices across the value chain.

In mid-March of 2023, the European Union fired a double salvo to make the EU economy more resilient and ensure robust raw material value chains, namely: the publication of the 5th critical raw materials (CRM, [1]) list and the proposed Critical Raw Materials Act (CRMA, [2–4]) further emphasizing the tools needed to achieve the objectives of the EU Green Deal [5] and to ensure a secure and sustainable supply of critical raw materials in and for the EU and to strengthen the resilience of its raw material value chain. Adopted by the Council of the EU by 30 June 2023 the CRMA emphasizes the need for the European Union to make greater use of its geological resources of strategic raw materials and to develop capacities to extract these materials so that at least 10% of the EU's annual consumption of strategic raw materials can be covered by indigenous primary raw materials. Article 18 of the drafted CRMA refers to national exploration programs for general exploration targeted at critical raw materials, and carrier minerals of critical raw materials by the EU Member States. The proposed concept of "strategic projects" requires a good understanding of the Earth's processes, history, and resources, as well as processing techniques, technological developments and demand and supply forecasts.

Publicly funded geological research and exploration in accordance with societal interests and rules plays a key role in the sustainable shaping of the European raw materials sector and the development of European raw materials policy. Geological research underpins all this and plays a vital role in our understanding of many of these key issues and is fundamental to be able to achieve the demanding objectives set out in these EU proposals. By understanding the geological processes and resources of our planet, we can make informed decisions and work towards a more sustainable and resilient future. This resilient future needs to be anchored on sound, robust, open, up to date, homogenized minerals data intelligence. Geological Survey Organizations (GSO) of Europe play a key role in generating, compiling, gathering and storing the most up-to-date information as well as long-term data series on raw materials at national and regional levels [6]. They hold historical data and information, strive to update national geological data using state-of-the-art methods, and in many cases provide commodity information on potential mineral targets and on demand trends. Much of this harmonized information and shared data are now harvested from GSO and made publicly accessible through the European Geological Data Infrastructure (EGDI) of the EuroGeoSurveys (Figure 1), which is the umbrella organization of Europe's national GSO [7,8]. To improve trans-national data interoperability, the European GSO have joined forces throughout a European Network Programme (ERA-NET Cofund action) "Establishing the European Geological Surveys Research Area to deliver a Geological Service for Europe (GeoERA)" that has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 731166 [9]. Under the GeoERA Raw Materials Theme, four scientific projects EuroLithos [10], FRAME [11], MINDeSEA [12] and MINTELL4EU [13] provide valuable and coherent information on onshore and offshore commodities in Europe with a special focus on CRM [14]. Supplementary Materials based on those projects and findings therein used in this contribution is accessible on EGDI (https://www.europe-geology.eu (accessed on 30. June 2023)). Many initiatives from GeoERA continue under the new network program "Geological Service for Europe (GSEU)" [15] which, as GeoERA, is a cooperation project involving almost all GSO of Europe.

This paper will provide some information on the rationale for further raw material prospection, exploration and mining of primary raw materials and mining residuals in Europe based on the outcome of the networking project GeoERA, focusing on the need for verified, homogenized data.

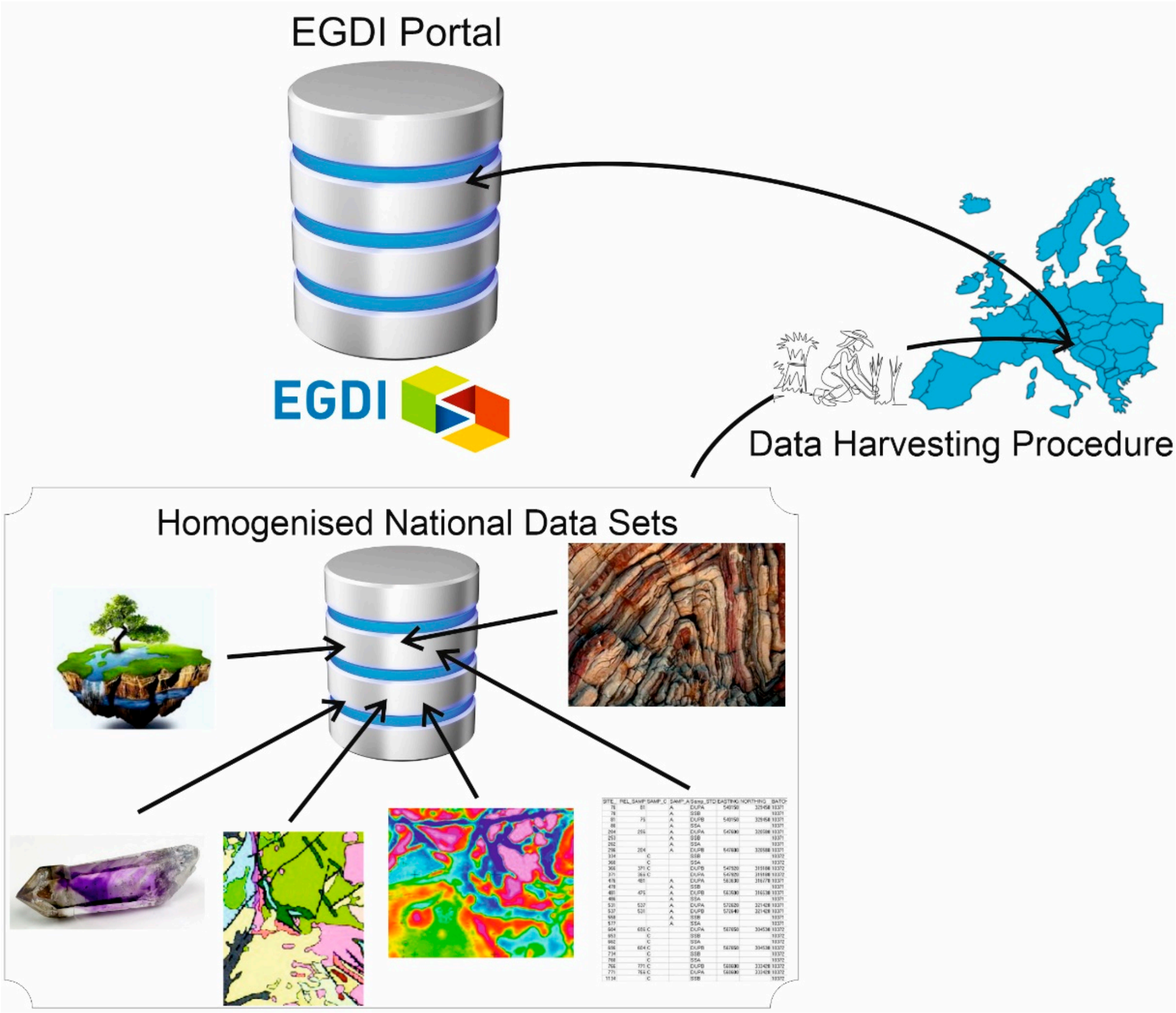

Figure 1. Simplified and idealized data pathway from GSO to EGDI. Credit to Špela Kumelj and the MINTELL4EU Team; courtesy of EuroGeoSurvey.

2. Benefits of Reassessing Historical Mining Sites and Data

There are many reasons why it is worthwhile to look at the past European mining regions, the long history of European mining and accompanying technical achievements, even if mining is not currently practiced in many of the old-established mining regions. The reasons for this are manifold, such as currently low profitability, lack of technical solutions, lack of risk capital or lack of social acceptance. These are variables and a recurrent assessment therefore makes sense.

Several, often well-preserved, mining sites in Saxony, Germany, for example, are re-assessed for other CRM (e.g., Li), while also taking advantage of the exploration campaigns in the communist times. The responsible mining authority of the German Free State Saxon provided periodical updates on the current situation concerning exploration and mining licenses online [16]. In this region, science-based mining reports dating back to medieval times due to the famous mineralogist and metallurgist known as Georgius Agricola (Georg Bauer), the author of *De re metallica libri XII* [17]. This magnum opus is an early systematic account of the entirety of mining and metallurgy, which initiated the development of the mining sciences and remained an unrivaled model over the centuries. However, modern geoscientific methods for exploration, extraction and beneficiation push the limits of what is seen to be economical and ecological valid further. This has consequences for the concept of statistical ranges of reserves. The statistical range represents the ratio of the approved reserves of a raw material group to the annual production volume. The static range is thus an indicator of the current state of knowledge or actual status. It is therefore subject to a certain degree of uncertainty, and depends as much on technical developments as on societal conditions. Several studies over the last decade proved that European bedrock still carries significant potential for several raw materials important for our economies, including such rocks that host CRM [18–22]. The CRMA may stimulate reassessing those regions and may set incentives to explore the subsurface further.

It is a common practice to sift through historical data and drill cores and to supplement findings with field work and modern analytical methods. Even in areas that are considered well known, promising sites can be newly identified in this way, which can also provide previously unexplored raw materials if requirements change. Moreover, what seems to be exhausted or waste might become a valuable source of raw materials today or in the future. In that respect, the Iberian Pyrite Belt, which hosts massive sulfide deposits mined most extensively in the 19th century, has been revisited for REE in its acid mine drainages (AMD) [23,24]. Still today, the Neves-Corvo mine in Portugal is being mined by Lundin Mining Corp. to produce copper, zinc and lead, for example. The company is also mining the Swedish Zinkgruvan mine for zinc, lead and copper.

In Finland, systematic research on the potential of extractive waste as a secondary resource of raw materials is currently taking place [25]. Together with case studies amongst others from Sweden, France and Serbia, mine tailings are being reinvestigated for its critical and strategic raw material potential supplemented by case studies in the Balkan Region [26,27]. Those ongoing studies are part of the EU-financed research project Future Availability of Secondary Raw Materials (FutuRaM) [28] that will provide additional mineral information on the potential new source of CRM. To lift this potential further, the right technological collection, sorting, separation and possessing solutions, as well as the appropriate regulatory framework, need to be in place. By applying the UNFC scheme on a set of cases, FutuRaM will pinpoint specific shortfalls.

Due, among other things, to globalization in the raw materials industry, the development of gigantic deposits overseas and the high aftercare costs of mining, many of Europe's historic mining sites are only preserved because of their UNESCO World Heritage status. This applies, for example, to the traditional mining regions of Erzgebirge and Harz, (DE), Lousal (PT), and Røros (NO). They are, therefore, not accessible for raw material extraction [29].

These ups-and-downs can be seen in many places, and are caused by changing requirements on the demand site, developments in technologies from exploration, processing to manufacturing and the end-of-life of a product, as well as changings philosophies, social and environmental requirements. Frequent shifts on the demand side are often caused by developments in material science. The modern rare earth industry, for example, could only develop when large quantities of high-purity rare earth elements became available for electronic, magnetic, phosphor and optical applications.

The history of mining in the Laurion region is an illustrative example for the benefit of reassessing historical sites and making benefit from mining residuals. Laurion's silver deposits were mined, smelted and supplied ancient Athens with silver talers. The famous "owl coins" were an important reserve currency in classical antiquity and also financed the construction of the Athens fleet. Historians attribute the decisive victory over the Persians at Salamis to the fleet. Through reassessing the Laurion region during the foundation of Greece as a nation state in the early 19th century, the raw material potential was reassessed. Although the deposits for the mining of silver were classified as economically insignificant at the time, the ancient mountain heaps ("Ekvolade"), wash sands ("Plynites") and lead slags were not. Their economic potential was raised through recycling. Between 1877 and 1917, an estimated 1.35 million tons of lead were recovered from the old mining residues, as well as zinc, iron and manganese. Mining continued here until 1977. As a result of these mining enterprises, Southeast Attica developed into a thriving industrial landscape in the 19th century, with the most developed infrastructure in Greece [30].

Even though these are historic examples, they illustrate the ongoing challenges of raw material supply and demand in human history. The geological survey of the country and the recommendations for the designation for the use of the geosphere are, therefore, a permanent task for the GSO of a country or a region, considering the changed framework conditions.

3. Benefits of Sound Geological Data

For the purpose of this study, sound geological data refers to accurate and reliable information collected through various scientific methods and techniques about the Earth's geology. It encompasses data related to the composition, structure, rock formations, sedimentary layers, and their properties, such as mineral composition, texture, and stratigraphy and history of rocks, minerals, fossils, and other geological features and processes. Additionally, sound geological data includes the analysis, verification and homogenization of the data so that one continent "speaks in the same geological language", and is crucial for understanding and interpreting the Earth's past and present conditions, as well as predicting future geological events.

Sound geological data is a precursor for: (a) *Resource planning and management*: Access to accurate and comprehensive mineral data intelligence enables governments, industries, and stakeholders to make informed decisions regarding resource planning and management. It helps identify potential mineral deposits, assess their economic viability, and plan for their sustainable extraction and utilization. (b) *Supply chain resilience*: A resilient future requires a secure and resilient supply chain for critical minerals. Mineral data intelligence helps identify potential sources of critical minerals, assess the reliability of supply, and develop strategies to diversify sources and reduce dependency on a single region or supplier. This knowledge is vital for maintaining stable supply chains and mitigating the risks of supply disruptions. (c) *Sustainable development*: Homogenized mineral data intelligence plays a key role in promoting sustainable development practices. It helps assess the environmental impact of mineral extraction, monitor compliance with environmental regulations, and identify opportunities for minimizing resource consumption and waste generation. By integrating environmental considerations into decision-making processes, mineral data intelligence supports sustainable mining practices and reduces the industry's ecological footprint. (d) *Technological innovation*: open and up-to-date mineral data intelligence supports technological innovation and research and development efforts. (e) *Transparency and accountability*: Sound and open minerals data intelligence promotes transparency and accountability in the mining sector. It helps track mineral production, exports, and revenues, preventing illegal mining activities, smuggling, and corruption. By providing reliable and accessible data, it enables stakeholders to monitor and ensure compliance with social, environmental, and ethical standards in the mining industry. (f) *Collaboration and knowledge sharing*: Homogenized mineral data intelligence fosters collaboration and knowledge sharing among stakeholders. It facilitates the exchange of information and best practices, enabling governments, industries, researchers and communities to learn from each other's experiences and successes. By promoting collaboration, mineral data intelligence supports innovation, efficiency, and sustainability in the mineral sector.

The GSO in Europe have long experienced cooperation through the EU-cofinanced networking project GeoERA. The GeoERA scientific project Mintell4EU facilitated the integration of project-generated data into national datasets and subsequently the transfer to the central database EGDI. Developed through Mintell4EU the GSO Slovenia, GeoZS, has developed a data harvesting system that allows GSO easily to upload their national data in EGDI. Details concerning the process of collection and harmonization of data for updating and expanding datasets and the European knowledge base, the structure, and the content hosted by EGDI is described elsewhere [6]. To improve the data harmonization of existing national databases and the European Minerals Inventory, established within Mintell4EU covered mineral occurrences and mines of 31 countries, Mintell4EU tested the United

Nations Framework Classification for Resources (UNFC) application through 19 test cases on 13 commodities and in nine countries [31]. Those experiences led to recommendations shared with the European Commission, DG GROW and the UNECE, and take into account in the guidance document "UNFC for Europe" [32]. As one of the leading EU countries in applying UNFC to the national database, Finland has already classified its strategic raw materials according to UNFC, as has Romania [33].

4. Raw Material Potential

The project GeoERA with thematic focus on raw materials is a building block to a common understanding of European raw materials potential [14]. However, and with courtesy by the GeoERA consortium it is worth to present an excerpt of the key findings here. Looking into existing datasets, making use of new information and combining knowledge to gain new assets is a steppingstone towards Europe's raw material resilience. The GeoERA scientific project Forecasting and assessing Europe's strategic raw materials needs (FRAME) built on previous and current pan-European and national databases. FRAME increased strategic and CRM knowledge through a compilation of metallogenic maps for critical raw materials in Europe [34]. These cover related metal associations and mineral potential both on land and offshore; the latter by another GeoERA project Seabed Mineral Deposits in European Seas: Metallogeny and Geological Potential for Strategic and Critical Raw Materials (MINDeSEA) (Figure 2).

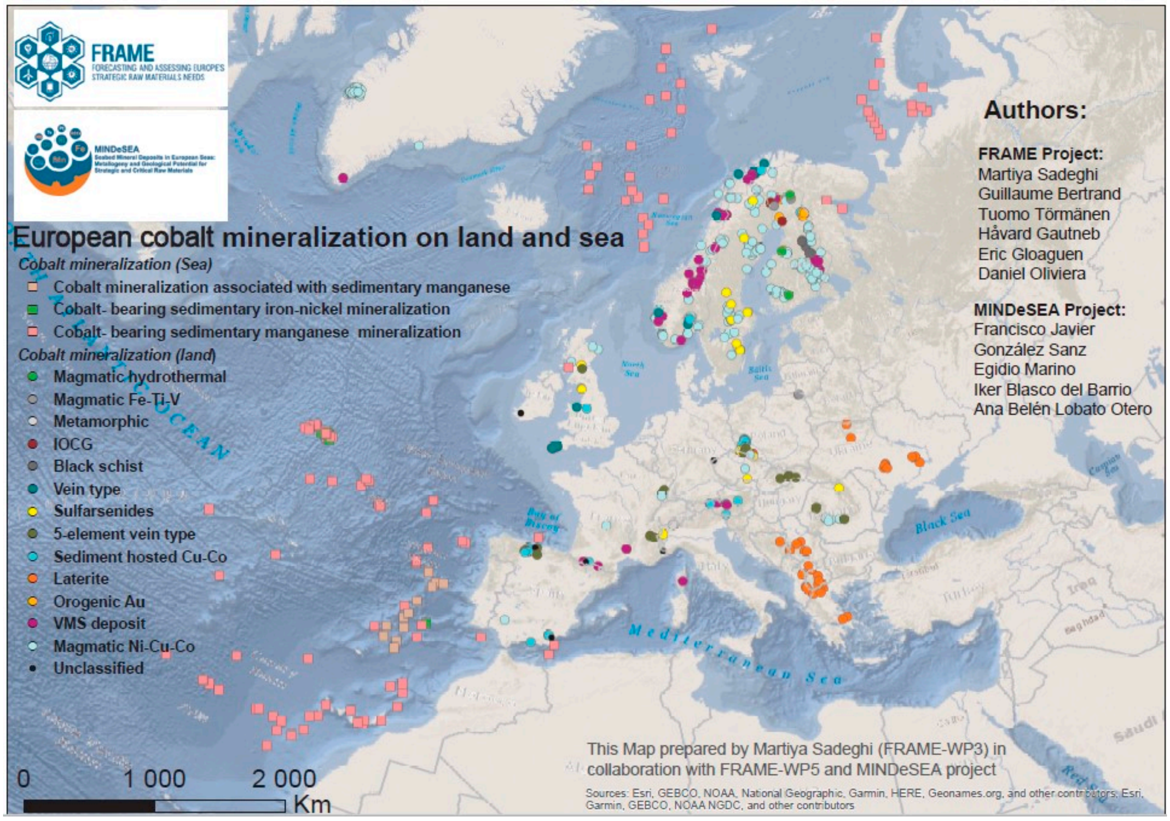

Figure 2. On- and offshore map of known cobalt (Co) mineralization in Europe. Credit to Martiya Sadeghi, Guillaume Bertrand, Tuomo Törmänen, Håvard Gautneb, Eric Gloaguen, and Daniel de Oliveira (FRAME Project) and Francisco Javier González Sanz, Egidio Marino, Iker Blasco del Barrio and Ana Belén lobato Otero (MINDeSEA project); courtesy of the GeoERA FRAME project and the GeoERA MINDeSEA project.

Secondary resources, in terms of historical mining wastes and potential by-products, were also considered [35–38]. The mineral resources targeted extend beyond the current EU CRM list and include minerals and metals (e.g., lithium (Li), tantalum (Ta), and niobium (Nb)) that are strategic for the European downstream industry in the mid- to long-term [39,40]. Assessments for CRM on the national basis, such as for Germany, Poland, Portugal, the Nordic Countries [41–44] are the basis for the findings.

One of the more innovative actions of FRAME was the production, through predictability studies, of maps of areas of higher mineral potential. The core objectives were (a) to identify conditions and processes involved in the formation of strategic and CRM-potential deposits and develop conceptual models for their formation; (b) predictive targeting, based on GIS exploration tools, of high potential mineral provinces and mining districts; (c) displaying and distributing maps and descriptions on the Information Platform, and (d) highlighting mineral resources critical to high-tech and downstream sectors. FRAME has also highlighted the regions with the greatest potential within the respective project boundaries for selected raw materials using both old and new data [45–47]. Compiling and publishing Pan-European metallogenic maps (Figure 3) for the various areas while unlocking old data is an innovative aspect for many GSOs.

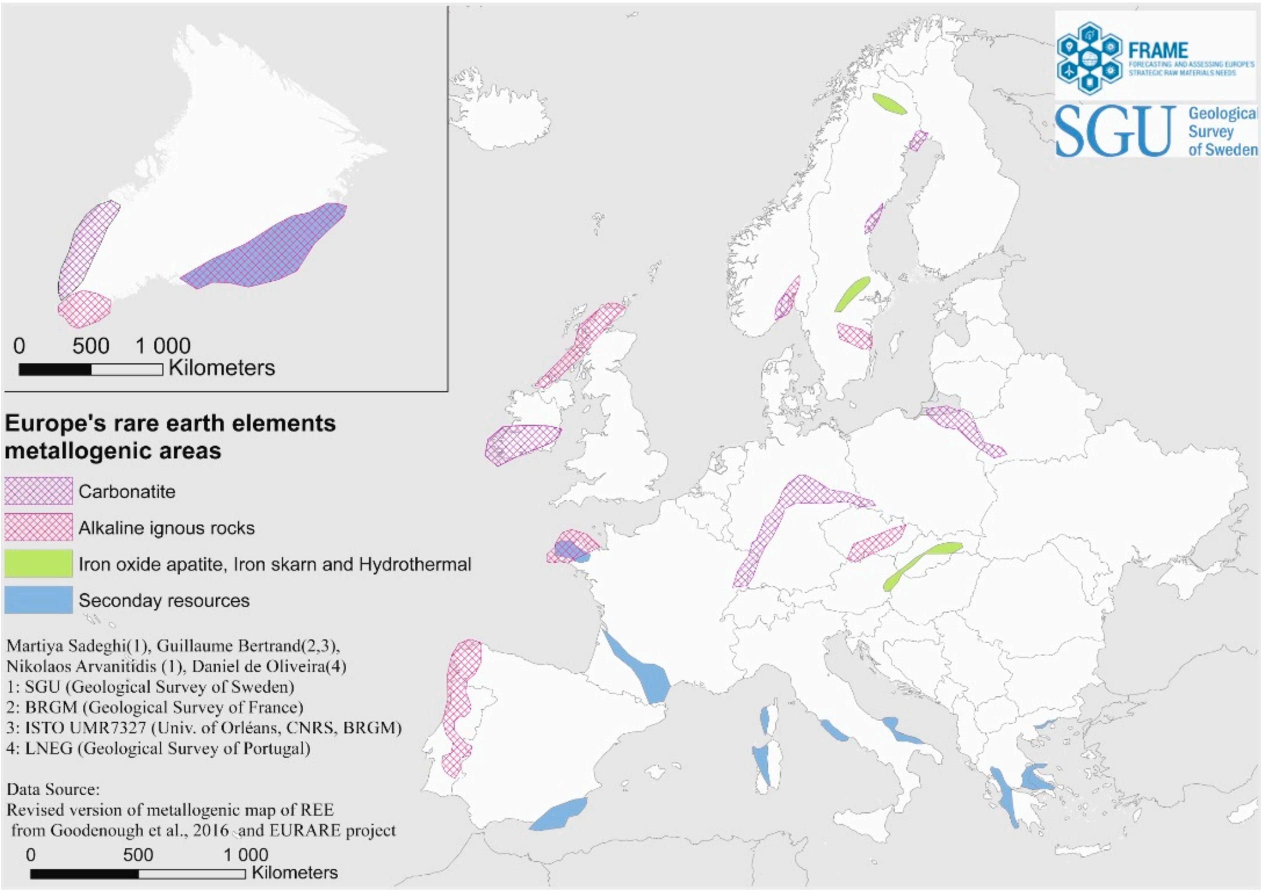

Figure 3. Example of a metallogenic map for rare earth elements in Europe. The delimitation of each area is based on similar geological features and formations integrated with known mineral deposits and occurrences. Credit to Martiya Sadeghi, Guillaume Bertrand, Nikolaos Arvanitidis and Daniel de Oliveira; courtesy of the GeoERA FRAME project [48].

The mineral favorability procedure named Cell Based Association (CBA), which compares different attributes from different datasets, was used to provide enhanced favorability maps as well [48–50]. In the areas studied, the highest mineral potential of that area is identified (Figure 4). It provides a tool to improve effectiveness and efficiency of future investments in exploration.

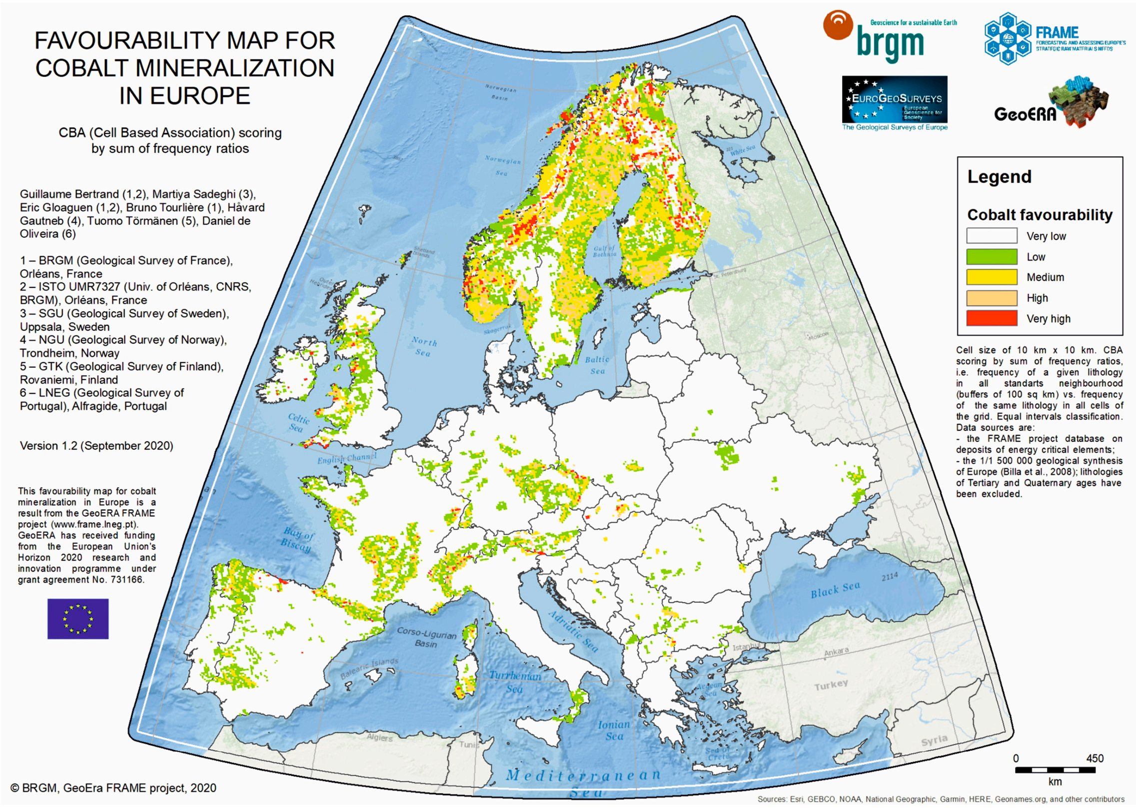

Figure 4. Example of a prospectivity map for Co in Europe, GeoERA scientific project FRAME. The likelihood of potentially finding a Co deposit is indicated by the color scale in the image. Credit to Guillaume Bertrand, Martiya Sadeghi, Eric Gloaguen, Bruno Tourilière and Daniel de Oliveira; courtesy of the GeoERA FRAME project [51].

In addition, the close cooperation with MINDeSEA—the GeoERA scientific project on marine raw materials—permitted the integration of both onshore and offshore prospectivity mapping for the first time in Europe, providing further information on the distribution of selected CRMs in the European seas [52]. In this way, targets for exploration investment were identified, supported by detailed metallogenic studies. FRAME has used high-resolution analytical techniques to explore strategic and critical raw materials as an essential part of targeting resources, e.g., phosphate deposits [53]. The (high-resolution) mapping of the distribution of chemical elements in an ore can be used, for example, to develop general models, in situ evacuation techniques, or to improve beneficiation methods.

5. Concluding Remarks

Resourcing Europe from primary and secondary sources, building resilient value chains with refineries, smelters, manufacturers, repair and recycling is a crucial need in the EU as much for raw materials of strategic interest as for critical raw materials already noticed as such. The new list of raw materials and the CRMA takes note of that, for example.

The latest list of critical raw materials in the EU also refers to base metals also crucial to build the infrastructure for the green economic transition and shift in energy supply. Europe is not poor in raw materials, but falls short in production. Still today, Europe has valuable deposits of copper (e.g., Poland, Portugal, Spain, Bulgaria and Sweden), zinc and lead (e.g., Sweden, Ireland and Poland). Deposits hosting significant amounts of critical raw materials such as rare earth elements (Sweden), graphite (e.g., Austria, Czech Republic, Finland, Germany, Sweden, Norway), tungsten (Portugal), and boron (Serbia) [54–56]. The current demand for lithium has also lifted the race for lithium. Deposits are known in several places, including Czech Republic, Germany, Portugal, Serbia and Spain [57].

In addition, lithium may be extracted from brines (France, Germany) in the context of hydrothermal projects [58]. The most advanced overview on the current known potential of a region has been provided for the Nordic countries, also echoing their leading position in CRM supply to the EU [59–61].

However, the immense array of potential future geological deposits of many minerals—metallic and non-metallic ores—are in competition with deposits elsewhere to gain the risk capital for exploration and development before any exploitation can take place. Despite the fact that the Fennoscandian nickel deposits may also induce Europe's independence from imports, giant programs such as the development of deposits accompanied with the related down-stream industry in Indonesia are challenging competition.

Supplementary Materials: The following are available online at EGDI accessible on https://www.europe-geology.eu/ (accessed on 30 June 2023). GIS viewers for the GeoERA scientific projects (a) Mintell4EU (b) FRAME results; (c) MINDeSEA results, and (d) Eurolithos results, as well as an electronic Minerals Yearbook, Minerals Inventory and Tourist Mines across Europe established under the Mintell4EU project. The EGDI is also the home of further mineral resource data compiled by other joint projects, such as RESEERVE.

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