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FRAME is coming to an end

FRAME started out with very definite objectives that built on previously available data developed in past EU projects (e.g., M4EU, EuRare, ProSUM, PROMINE and SCRREEN). As we fast approach the end of the GeoERA projects, in which FRAME is included, many are the achievements and substantial leaps forward in information gathering, data harmonisation and new understanding of the European mineral scenario.

At the end of October, FRAME will come to an end with the satisfaction that it has surpassed several milestones and offered new scientific products to earth scientists in general, but also to decision makers in local, regional, national and central government agencies.

This issue of the newsletter is yet another brief look at some of the more innovative achievements and results within the FRAME project.

Outlining the cobalt and phosphor exploration potential areas and mineralisation in Europe: a collaboration between FRAME and MINDeSEA projects

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Introduction

One of the primary goals in FRAME project's WP3 (Critical and Strategic Raw Materials Map of Europe), in collaboration with other work packages of FRAME and other GeoERA projects, is to produce and present the mineralisation and potential areas for CRM in Europe. Identifying new resources of supply critical mineral potential on land and in the European seabed for CRM needed for energy transition, is crucial for the European Union. In this regard, identifying and mapping of the major metallogenic areas for different type of mineralisation is essential. The global demand for CRM and strategic minerals containing cobalt, phosphorous, rare earth elements, tellurium, manganese, nickel, lithium and copper, concurrent with the rapidly diminishing quality and quantity of land-based mined deposits, has placed the seafloor as a promising new frontier for the exploration of mineral resources.

To develop metallogenic research and models at regional and deposit scales, with special attention to strategic critical minerals, for which the EU's downstream industry is highly dependent in the mid- and long-term perspectives, one must go from the known to the unknown, or at least, less known. Collating this information into favourable terrains is absolutely necessary to be able to understand mineralisation at the various scales. The latter was one of FRAME's objectives as we will see developed below for phosphate and cobalt mineralisation.

The geological evolution of European terrains provided favourable conditions for the formation of a variety of

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mineral deposits in time and space. Distribution of metallogenic provinces strongly correlates with their tectonic settings and evolution.
The largest metallogenic provinces are shown in Figure 1. These include the Fennoscandian Shield, Caledonian province, Variscan province, Alpine province and Greenland comprising the Gardar and north Atlantic igneous provinces.

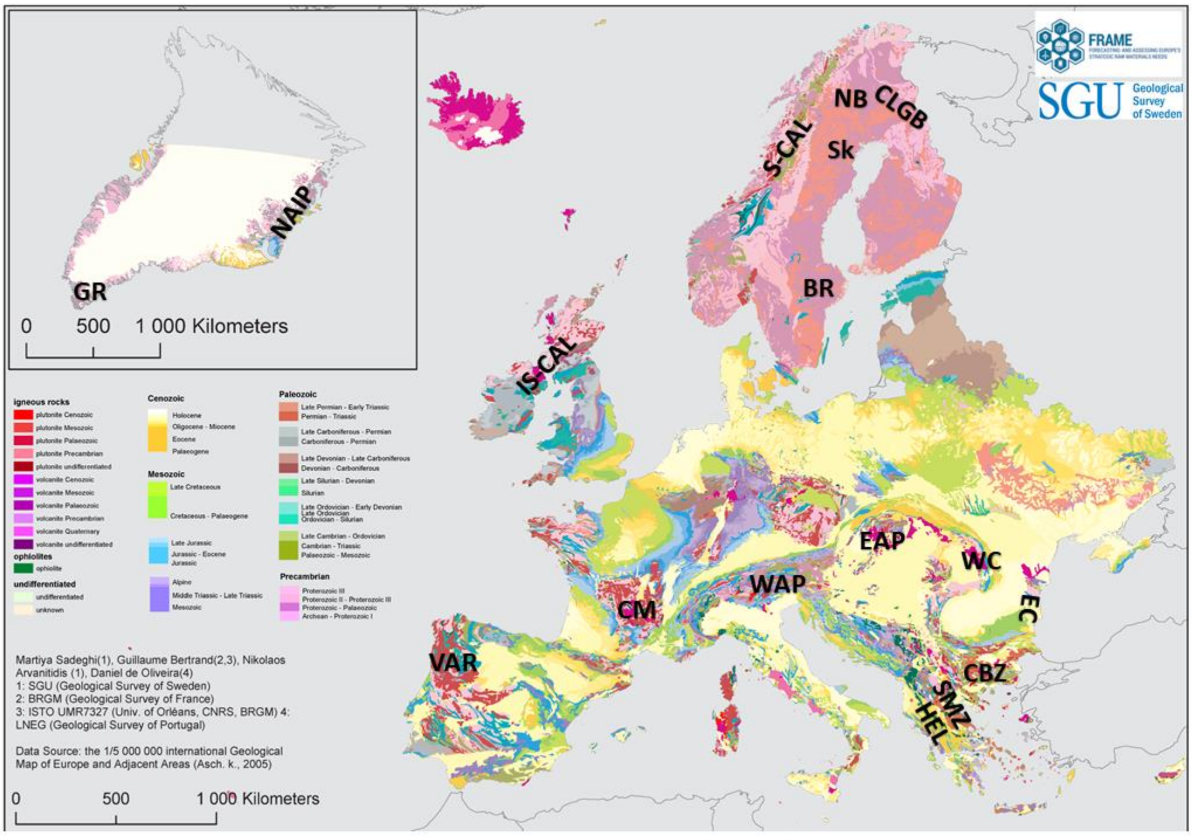

Figure 1. An overview on geological map of Europe and Greenland modified after Asch (2005) and the main metallogenetic areas in Europe. GLGB: central Lappland greenstone belt; NB: Norrbotten; Sk:Skellefte; BR: Bergslagen; S-CAL: Scandinavian Caledonides; IS-CAL: Ireland-Scotland Caledonides; EAP: Eastern Alpine province; WAP: Western Alpine province; WC: Western Carpathian; EC: Eastern Carpathian; CB: Carpathian-Balkan Zone; SMZ: Serbian-Macedonian Zone; HEL: Hellenides; CE: Central massif; VAR: Variscan metallogenic province; Gr: Gardar province; NAIP: North Atlantic Igneous Province.

Covering more than 70% of the planet, oceans represent a potentially promising new frontier for the exploration of mineral resources. Spanning a large diversity of environments and resource styles, including high- and low-temperature hydrothermal deposits (seafloor massive sulphides-SMS, sedimentary exhalative deposits-SEDEX), phosphorites, cobalt-rich ferromanganese crusts, manganese nodules and rare earth elements-rich muds, deep- sea deposits are particularly attractive for their polymetallic nature with high contents of transition, rare and critical elements. Moreover, shallow-water resources, like marine placer deposits, represent another source for many critical metals and gems. The seabed mineral resources host the largest reserves on Earth for some important metals like cobalt, lithium, tellurium, manganese, and the rare earth elements, critical for the industry (Figure 2).

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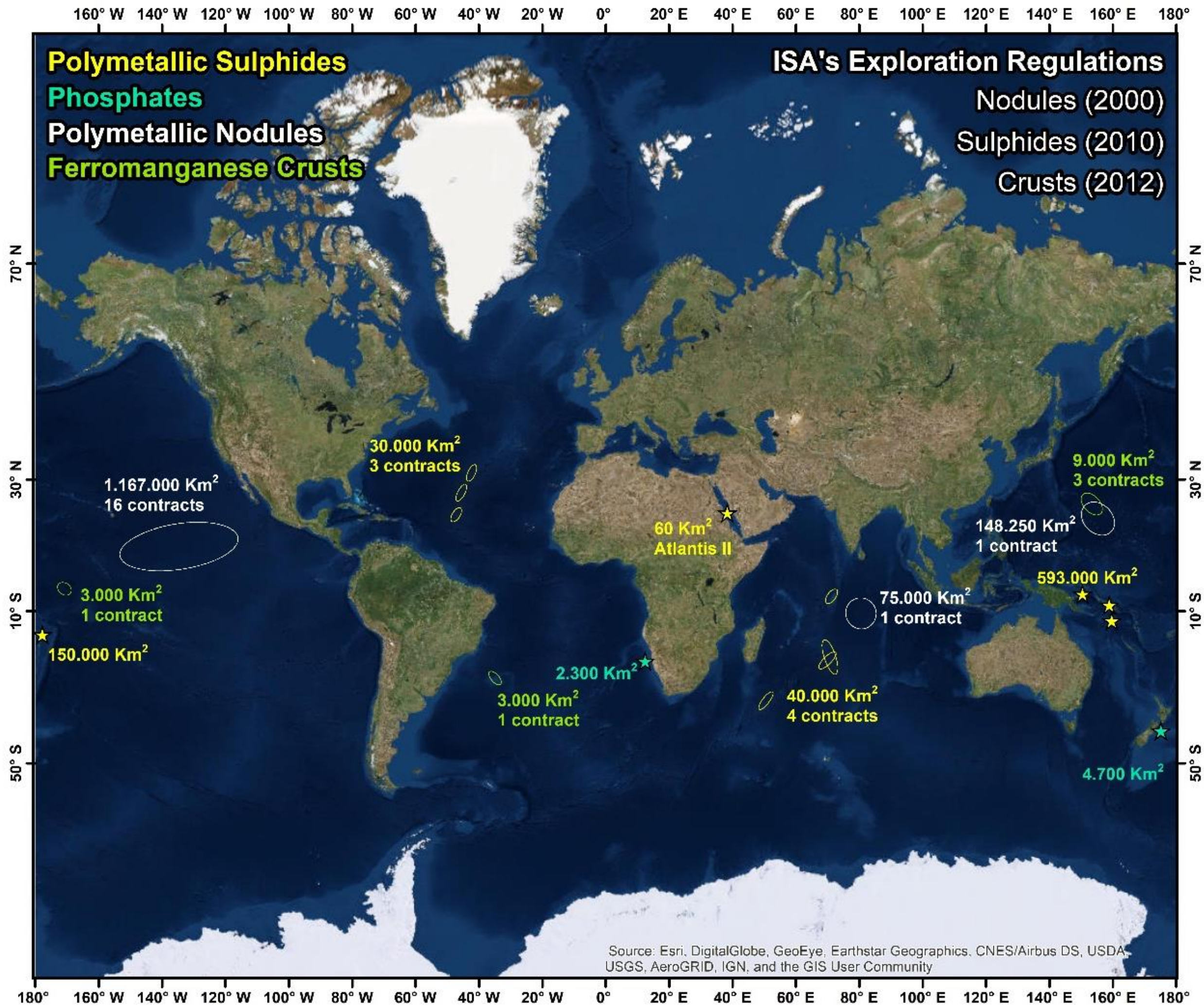

Figure 2. Global map of seabed minerals exploration present status.
The stars represent areas under national jurisdictions.
Modified from Hein et al. (2013).

Phosphate mineralization and metallogenic areas in European land and seabed

Phosphorus is essential for living plants and animals. It is mostly found as apatite and is principally used to produce fertilizers (82% of the production). Phosphorus is therefore needed to satisfy the growing demand for food related to the growth of the world population. An increase of about 2% per year in the global market is expected (European Commission, 2015).

In Europe, phosphate deposits and occurrences are abundant and widely distributed. They are igneous or sedimentary in origin and their age varies from the Archean to the Pleistocene. In the European seabed, can be found in different contents in all the submarine ferromanganese deposits but in general these contents are not viably minable. The only deposit that shows great contents of P is represented by marine phosphorites. Phosphorites are formed during diagenetic processes in different oceanic settings as lagoon/insular areas,

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continental margins and seamounts (McArthur et al., 1984; Hein et al., 2016).

Phosphate metallogenic areas in land may related to the carbonatite or alkaline complexes containing apatite (e.g., In Fennoscandian shield). Other small occurrences of phosphate associated with carbonatites are known in Italy and Germany, Unsaturated and saturated syenitic and alkali granitic igneous rocks and pegmatites, the Loch Borralan and Loch Loyal Silurian intrusions (Scotland, UK) host apatite-rich facies that present a potential regarding phosphate (Notholt and Highley, 1981; Walters et al., 2013). In Norway, the Neoproterozoic Rogaland Anorthosite Province constitutes one of the most promising targets regarding phosphate exploitation (Ihlen et al., 2014). In southern Norway, the Kodal deposit is found in the Permian Larvik Complex (Oslo Igneous Province). In Finland, the Paleoproterozoic Kauhajärvi gabbro and appinite at Vanttaus are intrusions enriched in apatite that could present an interest for future phosphate exploration (Kärkkäinen and Appelqvist, 1999; Sarapää et al., 2013). Most of the iron oxide apatite deposits in Europe are found in Sweden, with (i) the major mining areas in the northern Norrbotten district and in the Bergslagen district (Hallberg et al., 2006). The most important European apatite deposits of hydrothermal origin – and (at least spatially) associated with granite – are the post-Variscan quartz-apatite veins occurring in the southern Central Iberian Zone (mining district of Logrosan and Belvis-Navamoral; Vindel et al., 2014). In Sweden, the REE-P mineralization occurring at Olserum, Djupedal and Bersummen is present as veins and vein zones hosted in metasedimentary rocks. It is thought to be deposited from high temperature hydrothermal fluids, in connection with the granite (Andersson et al., 2019). Three main episodes of phosphogenesis are known during the Lower Paleozoic, the Upper Cretaceous, and the Tertiary. They led to the formation of deposits of major importance. Lower Paleozoic phosphorites constitute most of the phosphorites in Europe, testifying for the presence of a phosphogenic province within the Avalon and the Baltic Platforms. An important sedimentary phosphate unit of Upper Cretaceous age is known throughout the Paris and Mons Basins (France and Belgium), where it forms economic deposits of phosphatic chalk. The Cenozoic constitutes another major period of phosphogenesis leading to the formation of many deposits and occurrences in Europe (Arthur and Jenkyns, 1981). The largest are known in the area of Salento (Italy).

Today, the only known phosphorites deposits in the pan-European seas are located in the Macaronesia and Iberian Margin (Figure 3). Studied samples have been recovered in the north of Spain (Galicia Margin) but also in the southwest of Portugal and Spain (Gulf of Cadiz) and are essentially linked to the continental shelf, banks and plateaus (Figure 4) The presence of phosphorites has been also detected in several seamounts of the area, sometimes at the base of thick Fe-Mn crusts. The Cenozoic was the principal period of phosphogenesis for the European seafloor occurrences (González et al., 2016).

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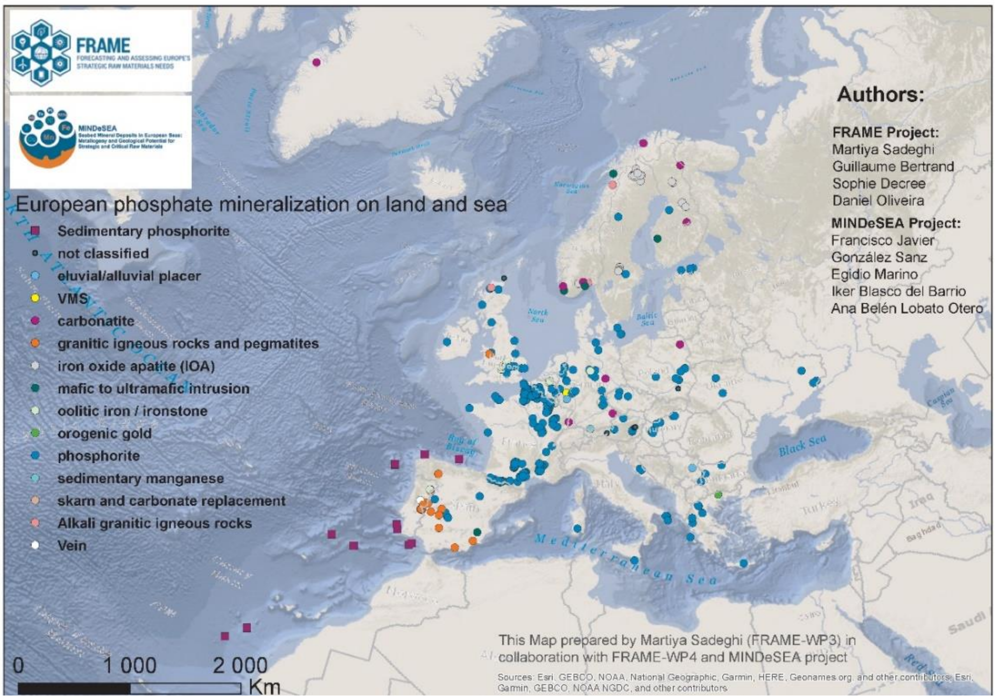

Figure 3. Map showing genetic classification of phosphate mineralization in land and European seabed (Sadeghi et al., 2020 a, b; Deliverable report FRAME D3.3).

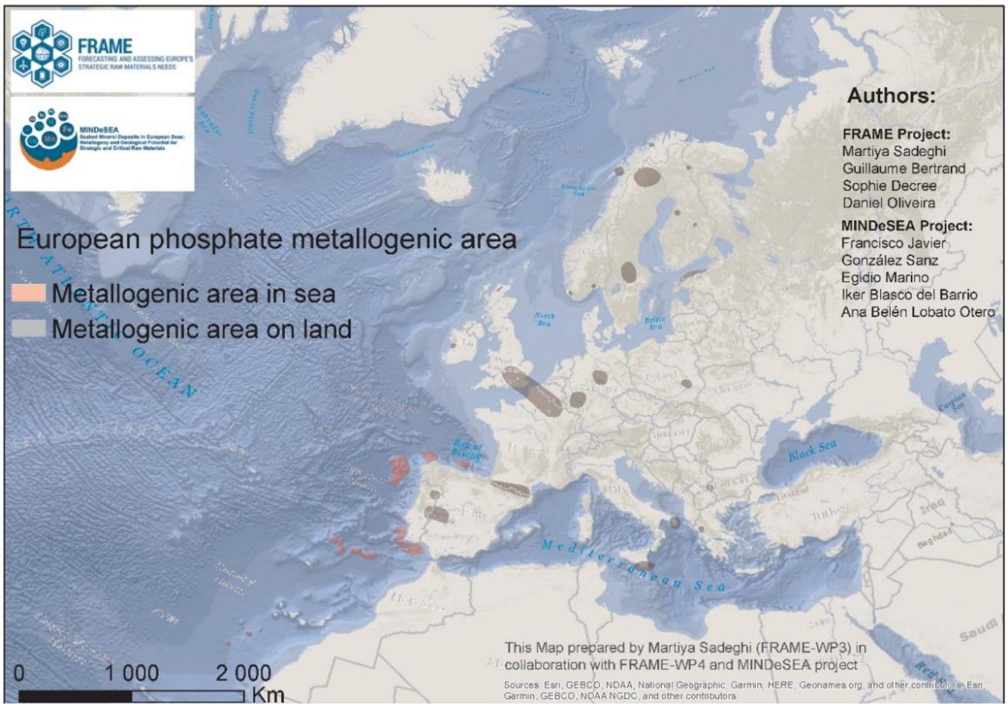

Figure 4. Map showing metallogenic area of phosphate mineralizations in land and European seabed (Sadeghi et al., 2020 a, b; Deliverable report FRAME D3.3).

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Cobalt mineralization and metallogenic areas in European land and seabed

In Europe, the most common deposit types are orthomagmatic Ni-Cu-Co deposits, volcanogenic Cu-Zn-sulfide deposits (VMS), Iron Oxide-Cu-Au deposits (IOCG), 5-element and other vein-type deposits, sediment-hosted Cu deposits, lateritic Ni-Co deposits and metasediment-hosted Cu-Au-Co deposits (e.g., Horn et al., 2021). Most of the cobalt bearing deposits and occurrences are clustered in Nordic countries (Finland, Sweden and Norway), with more scattered deposits occurring in southern and central Europe (Figure 5). Several lateritic deposits are clustered in the Balkans, Greece and Ukraine, but cobalt is generally not extracted from these deposits (Sadeghi et al., 2020 a, b).

Broadly, the following main cobalt metallogenic zones are a) The Fennoscandian shield: Norway, Sweden and Finland b) Greenland, c) The Balkans and Greece and d) SW and central Europe (Figure 6). Elsewhere in the Europe, small, mostly historic Co deposits and occurrences can be found related to variscan and Alpine orogenies, extending from Cantabrian mountains in NW Spain, through Pyrenees and France, northern Italy, Austria, Slovakia and Romania in the east. A cluster of Co-deposits also occur in the SW Poland. They represent a diverse suite of deposit types with sediment-hosted Cu-Co, 5-element vein type, VMS (to SEDEX) deposits and Co-sulfarsenide (vein) type being the most prominent types. In addition, magmatic Ni-Cu-Co deposits occur in Romania and lateritic Ni-Co deposits in SW Poland.

The Europeans seabeds, ferromanganese (Fe-Mn) deposits are represented essentially by hydrogenetic Fe-Mn crusts, diagenetic polymetallic (or manganese) nodules and hydrothermal sediments and stratabounds. These deposits can be found in all the oceans covering both abyssal plains (nodules and metalliferous sediments) or hard surfaces on seamounts, banks, ridges and plateaus (Fe-Mn crusts). The main mineral deposit for cobalt is represented by Fe-Mn crusts. Several studies on Fe-Mn crusts show that they concentrate important contents of Co, but also, depending on the genetic process and mineralogy, valuable contents of several other CRM like Te, Li, Nb, REE, etc. In pan-European seas these deposits are localized essentially in the Macaronesia and Iberian continental margins (Spain and Portugal) and in the Arctic Ocean (Norway, Iceland, Greenland and Russia) (Baturin et al., 2014; González et al., 2016; 2018; Marino et al., 2017; Hein et al., 2017; Konstantinova et al., 2017; EMODNET, 2020; MINDeSEA, 2020).

Three main metallogenic areas can be separated in pan-European seas: a) the Macaronesia and Iberian Margins, b) the north Atlantic and Arctic oceans, c) the Kara and Barents seas. In these areas can be found several marine seafloor elevations (knolls, seamounts, guyots, banks, plateaus) covered by Fe-Mn crusts with different Co concentrations (Sadeghi et al.,2020 a, b).

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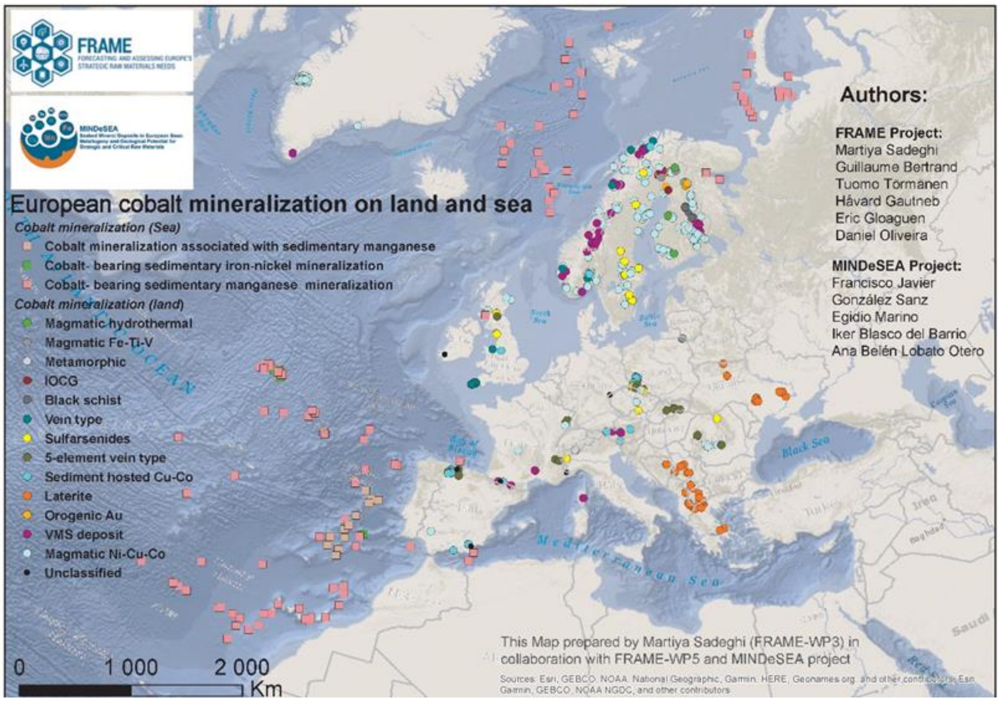

Figure 5. Map showing genetic classification of cobalt mineralization in land and European seabed (Sadeghi et al., 2020 a, b; Deliverable report FRAME D3.3).

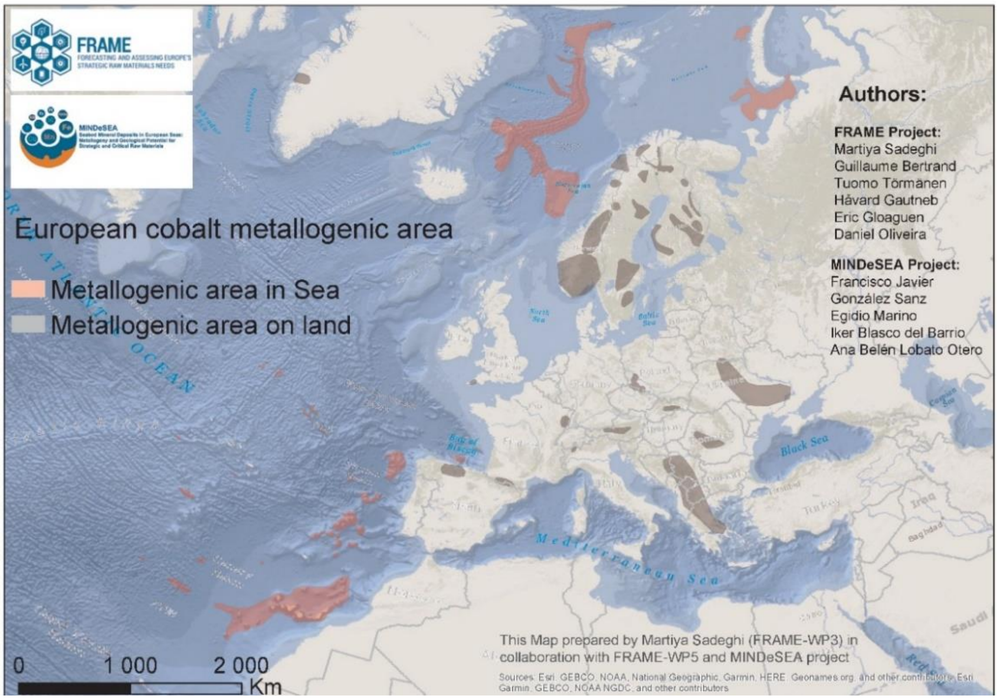

Figure 6. Map showing metallogenic area of cobalt mineralization in land and European seabed (Sadeghi et al., 2020 a, b; Deliverable report FRAME D3.3).

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Conclusion

The data collection on cobalt and phosphorous was carried out through the work package 4 and 5 in the FRAME project for continental Europe and through the MINDeSEA project for the European seabed. This data collection will allow the classification of Europe's according to the genetic types and this information can serve for the application of the United Framework Classification for Resource (UNFC) system.

The greatest potential for cobalt resources lies in laterite deposits in the Balkan, magmatic and black shale hosted deposits in Fennoscandia, and there is good potential for future investigation in stratiform sediment-hosted Cu-Co deposits in central and northern Europe. Significant concentration of cobalt may also occur on the seafloor associated with Mn nodules and cobalt-rich Fe-Mn crusts.

Phosphate rock resources occur principally as sedimentary marine phosphorites (e.g., Northern Estonia). Significant igneous occurrences are also located in the Europe associated with iron oxide apatite deposits (e.g., Kiruna in Sweden), and associated with alkaline complex (e.g., Loch Borralan) and granitic rocks (e.g. Logrosan district in Cáceres, Spain). In Austria and France are also areas for future targeting of this commodity. As igneous-related phosphate mineralizations show elevated REE and other critical metals compared to the sedimentary phosphorite, alkaline rocks might be a good targeting not only for phosphorous but also for other critical metals. There is good potential for sedimentary phosphate resources on the continental shelves and on seamounts in the south European Atlantic margins.

This study confirms that the potential for mineral resources in Europe is very significant and is a strong asset to the European community sovereignty. Beyond this, it highlights that this potential is not confined to onshore areas but also encompasses marine areas. Enhancing the knowledge of this onshore and offshore mineral potential of Europe is a strategic goal that should go beyond phosphate and cobalt, and that should strongly mobilize the scientific community in the coming years.

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Outlook on European niobium-tantalum mineralisation and exploration potential - FRAME WP6

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Work package 6 (WP6) of FRAME focuses on the chemically related elements niobium (Nb) and tantalum (Ta), which are two of the most particular critical metals (critical raw materials; CRM), of which specifically Ta, and to some extent associated Nb, are today extensively sourced from conflict mineral production in the central African region, locally known as “coltan”. Nb and Ta have unique properties and are essential components in a range of applications and products including electronics, steel alloys and superalloys, all of extensive importance to European (and global) industry. Overall, global Nb production today is based on pyrochlore minerals, i.e., Ca-Na-Nb-oxides from carbonatites and alkaline rocks, whereas Ta production is largely dependent on columbite-type and related minerals, i.e., mainly Fe-Mn-Nb-Ta-oxides (Fig. 1) from evolved granites and granitic pegmatite-aplite systems.

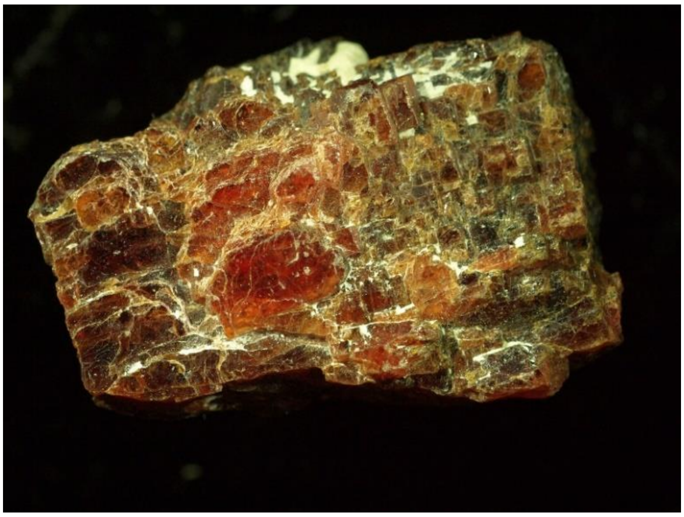

Figure 1. An important Ta mineral, tantalite-(Mn) in the form of a slightly corroded and broken, otherwise euhedral crystal with abundant red translucency characteristic of this species. White material is remnant clay from the weathering of the original host pegmatite feldspars. Image width c. 3 cm. Photo: E. Jonsson.

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WP6 has surveyed the pan-European distribution of Nb-Ta mineralisations (Fig. 2) in order to enhance their exploration interest and potential, as well as highlight the possibility of producing these critical metals ethically and indigenous to the EU. The results from WP6 are presented in four deliverable reports of which three have already been submitted. The final one is due at the end of the project in September 2021.

Deliverable D6.1 of WP6 is a comprehensive report on the distribution and systematics of Nb-Ta mineralisations in Europe, including case studies from Sweden and Spain. The results of this part of the work package also form the basis for developing recommendations for future exploration for these metals in Europe, in the form of deliverable D6.2.

Most the known European Nb-Ta mineralisations, and particularly those enriched in Ta, are associated with evolved granites and granitic pegmatites (and associated aplites). Granitic pegmatites and rare element granites occur in Palaeoproterozoic rocks of the Fennoscandian Shield and associated with younger (mostly Late Palaeozoic) granites and granitic pegmatite suites in continental Europe and Ireland.

In all these areas peraluminous granites together with granitic pegmatites of the more fractionated, so-called LCT-type (i.e., variably but typically highly enriched in lithium, caesium, and tantalum) are of primary importance. Mineralisations formed by hydrothermal systems associated with evolved granitic intrusions, e.g., greisen-type deposits, do also occur at some locations, but these are generally less common on the continental scale. The most important European Nb deposits are characteristically associated with alkaline to peralkaline (syenitic), mostly plutonic rocks and carbonatites which have primarily formed in intra-continental rift-settings.

Secondary deposits (mainly in the form of placers) also occur in Europe, but these have a more restricted distribution than the primary deposit types. Occurrences of this type are known from the Iberian Peninsula, central Europe and Ukraine.

Another objective of WP6 is to briefly highlight and discuss conflict minerals in the sense of Nb-Ta production in central Africa (deliverable D6.3). The need for European initiatives to assist in the improvement of the conditions of mineral production in this region cannot be underscored enough and the issue at hand remains a very significant challenge.

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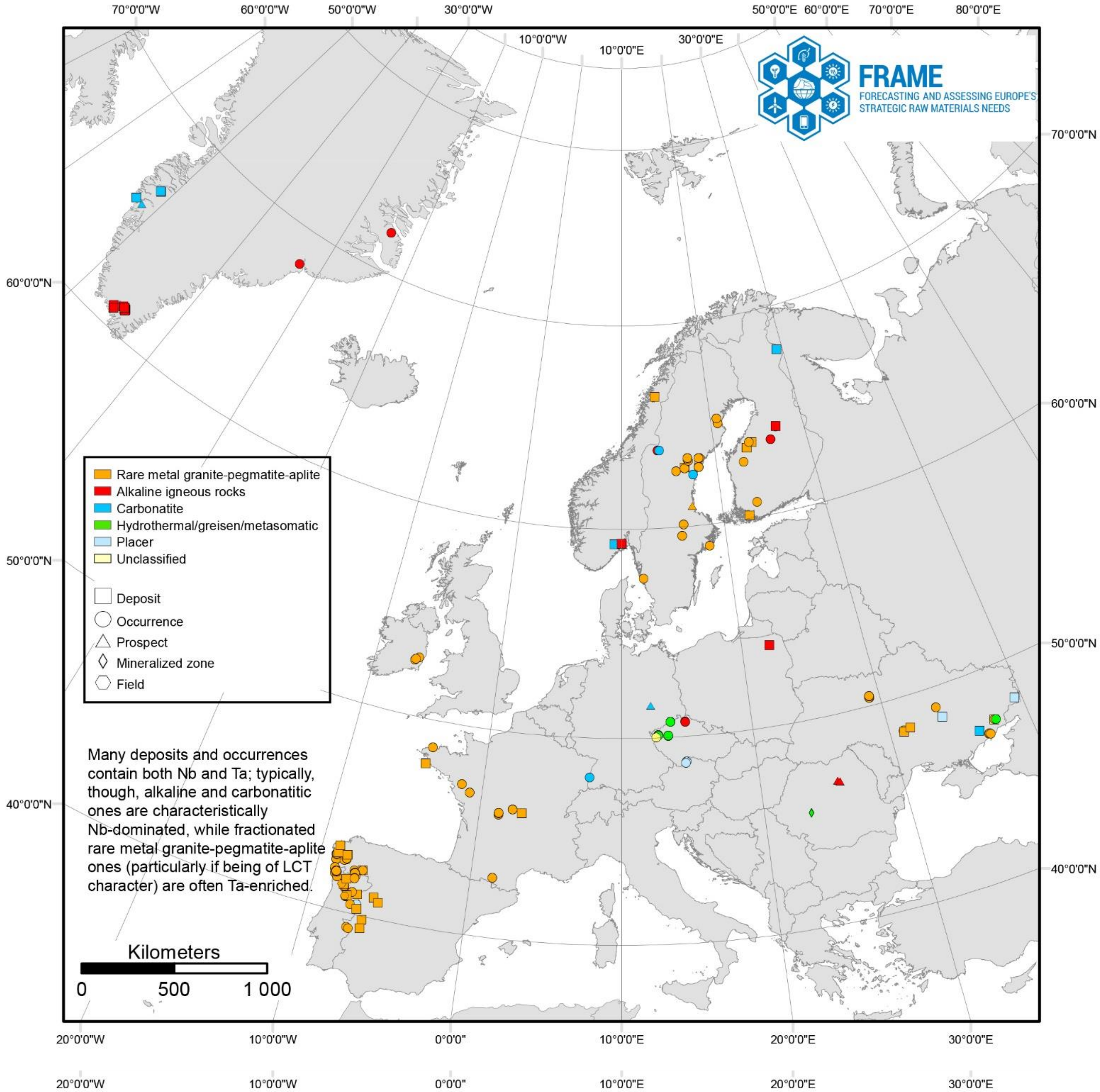

Figure 2. Nb and Ta mineralisations in Europe grouped by deposit type. The data is compiled from existing data in pan-European databases (Minerals4EU, EURARE, and ProMine) as well as national geological survey databases. Data on some deposits originate from external sources such as exploration companies and publications.

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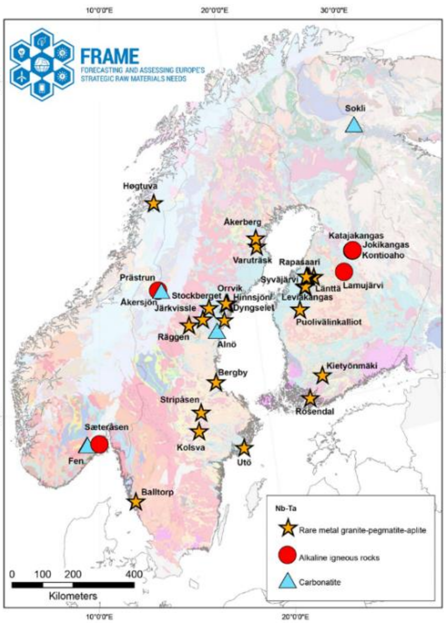
Focus regions

Two focus regions were selected in WP6: the Swedish part of the Fennoscandian Shield and the Iberian Variscan Massif (Fig. 3). These two areas represent regions that are very contrasting in terms of geological history, age and, in part, types of mineralisations, but there are also similarities. Some of the deposits in Spain and Portugal have been exploited previously for Sn, Ta-Nb, and/or W and have recently been subject to renewed interest from exploration and mining companies.



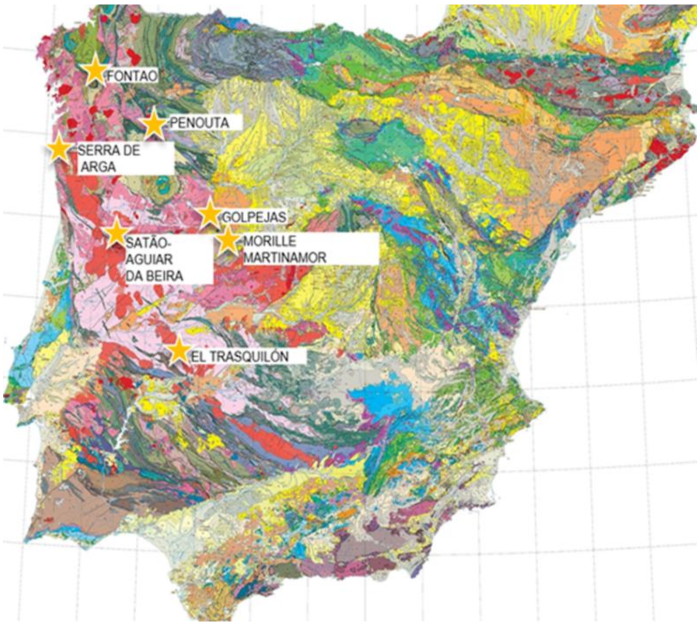


Figure 3. Nb-Ta mineralisations of Fennoscandia (left). Selected mineralisations of the Iberian Peninsula (right). The data is compiled from existing data in pan-European databases (Minerals4EU, EURARE, and ProMine) as well as national geological survey databases. Data on some deposits originate from external sources such as exploration companies and academic institutions.

Highlighted mineral systems

The Nb-Ta mineralisations of the Iberian Peninsula belong to the southwestern extension of the European Variscan Belt. The most relevant Nb-Ta deposits in Spain are those in which mineralisation occurs in small granites, as it appears in the deposits of Golpejas, El Trasquilón, in some occurrences of the Morille-Martinamor district, Fontao and Penouta. These deposits have been exploited previously for Sn, Ta-Nb, and/or W. In Portugal the Nb-Ta mineralisations are located in the northern part of the country and also comprise Variscan granitic rocks and pegmatites.

The majority of Nb-Ta mineralisations in Sweden are hosted by LCT-type (lithium-cesium-tantalum-enriched) granitic pegmatites that occur mainly in regions featuring abundant Palaeoproterozoic low to lower medium-grade metamorphosed metasedimentary rocks and associated S-type granites.

NYF-type (niobium-yttrium-fluorine-enriched) granitic pegmatites occur as individual dykes and fields throughout the Proterozoic bedrock of Sweden; notably the discovery location of tantalum was one of these granitic pegmatites. Research has focused on a few selected Swedish deposits and occurrences including Järkvissle, Räggen and Bergby in central Sweden, as well as Stripåsen and Utö as well as other rare-element pegmatites in the Bergslagen province, south central Sweden.

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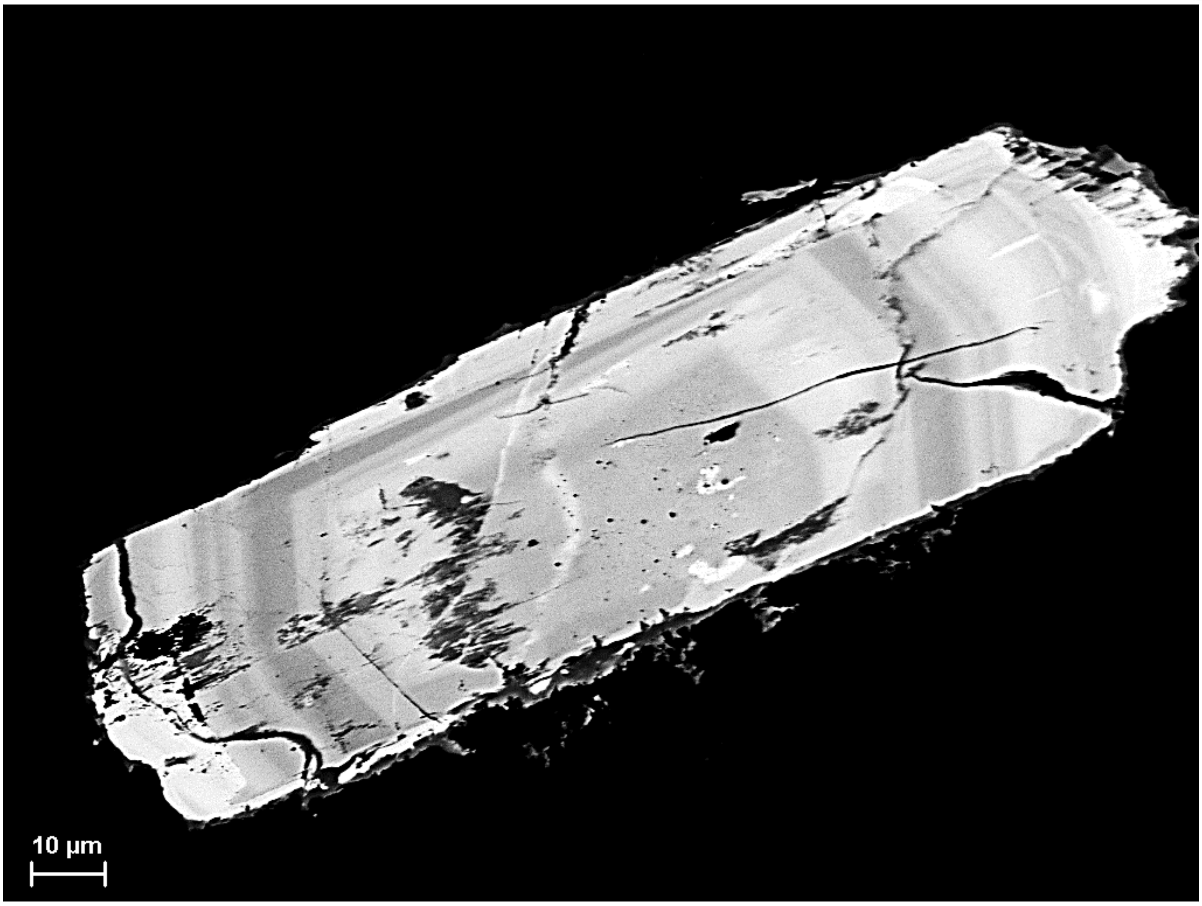

Figure 4. BSE image of a euhedral isolated crystal of tantalite-(Mn) from the LCT-pegmatite-aplite system at Bergby, Sweden´s most recently discovered Li-Ta-mineralisation (2007). The crystal exhibits a well-developed and symmetrical magmatic (chemical) growth zonation pattern. The most Ta-enriched zones are BSE-lighter/whiter. SEM-photo: E. Jonsson.

Exploration potential

On the continental scale the best exploration potential for Nb and Ta in Europe is related to the following genetic types, geological settings and regions:

Rare element granites, granitic pegmatites and aplites
Of particular importance with respect to Ta are specific suites of peraluminous granites and particularly their associated granitic pegmatite-aplite systems belonging to the LCT family. The best potential exists in orogenic belts with metamorphic terranes featuring late to post- orogenic granitic rocks, such as the Variscan provinces of south, west, central, and east Europe, and the Svecokarelian orogen of the Fennoscandian Shield.

- The Variscan Galicia-Centro Iberian Pegmatitic Province including the Central-Iberian Zone (CIZ) and the Galicia Trás-os-Montes Zone (GTMZ).
- The Massif Central and Armorican massif of France.
- The Bothnian basin and allied metasedimentary regions of the Fennoscandian Shield where groupings of LCT pegmatites occur in low to medium-grade (volcano) sedimentary successions associated with late-Svecokarelian, S-type granites.
- The Central and south-eastern part of the Ukrainian shield.

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Alkaline igneous rocks and carbonatites

Alkaline rocks and carbonatites may occur together and are known from areas associated with extensional tectonics and continental rifting settings. Carbonatites typically form relatively small intrusions or complexes. Specifically, Nb is often hosted by carbonatitic as well as alkaline syenitic rocks.

The most important regions hosting carbonatites with Nb (Ta) potential:

- West Greenland.
- The Fennoscandian Shield (e.g., Sokli, Finland and Fen, Norway).
- The Ukrainian shield.

Important regions hosting alkaline igneous rocks with Nb-Ta potential:

- South and East Greenland.
- Northeast Poland and the Eastern Carpathians.

Future European extraction of Nb-Ta

Domestic future EU mine production of Nb-Ta is most likely in cases of mineral deposits where Nb and/or Ta can be extracted as by-product of other mining/metal production. Some Li, Sn-W and REE deposits where Nb and/or Ta could add value to the operation are potential candidates. Alkaline complexes and carbonatites in Greenland host large deposits with critical metals including both Nb-Ta and REE.

Both primary and secondary resources including old tailings of Sn mining operations may have potential for Ta-extraction. A current and very relevant European example is the Penouta mine in Galicia (Spain), where the company Strategic Minerals Spain has started the processing of tailings from waste-rock heaps and ponds of the old Sn mine.

The ongoing transition to a sustainable, climate-neutral society has increased the demand for battery metals which has resulted in a strong focus on lithium demand, which can in turn provide incentives for exploration, developing new projects or to restart closed mines with Li and associated Ta (and Nb) resources.

Data collection, definition and implementation of methodologies - FRAME WP8

Lídia Quental (LNEG), Aurete Pereira (LNEG)

Data collection, definition and implementation of methodologies, have been undertaken throughout all the WPs in FRAME pursuing the objectives of the project.

In WP8, the aim is to gather all the products in the other WPs (3,4,5,6 and 7) and make them available through a large dissemination platform, namely the European Geological Data Infrastructure (EGDI) and the pre-requisites for this delivery imply alignment with the specifications of the GIP-P project. These specifications concern the database model, codelists, data formats and related metadata to obtain standardized and harmonized products throughout all the GeoERA RM projects, according to the INSPIRE directive requirements.
Until now FRAME has delivered to EGDI two categories of data:

- Structured datasets (18)
- Unstructured datasets (57)

In the first, the format was geopackage, while in the second are PDF (33), DOI (23) and CSV (1), all focused on depicting the main scientific project achievements.

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Until now, WP8 organized, prepared and delivered to EGDI platform 18 GeoPackages from a total of 25. The maps are distributed by four main groups of products on critical raw materials in Europe: 1) Metallogenic maps (9) 2) Mineral occurrences/deposits spatial distribution on land and the marine environment (8) 3) Potential/ prospectivity maps (1), and 4) Historical mine sites in Europe (ongoing).

An example is given in figure A of the spatial distribution of the cobalt mineralization occurrences map, aligned with the MINdeSEA project, figure B depicts the REE metallogenetic map of Europe, and figure C the associated prospectivity map.

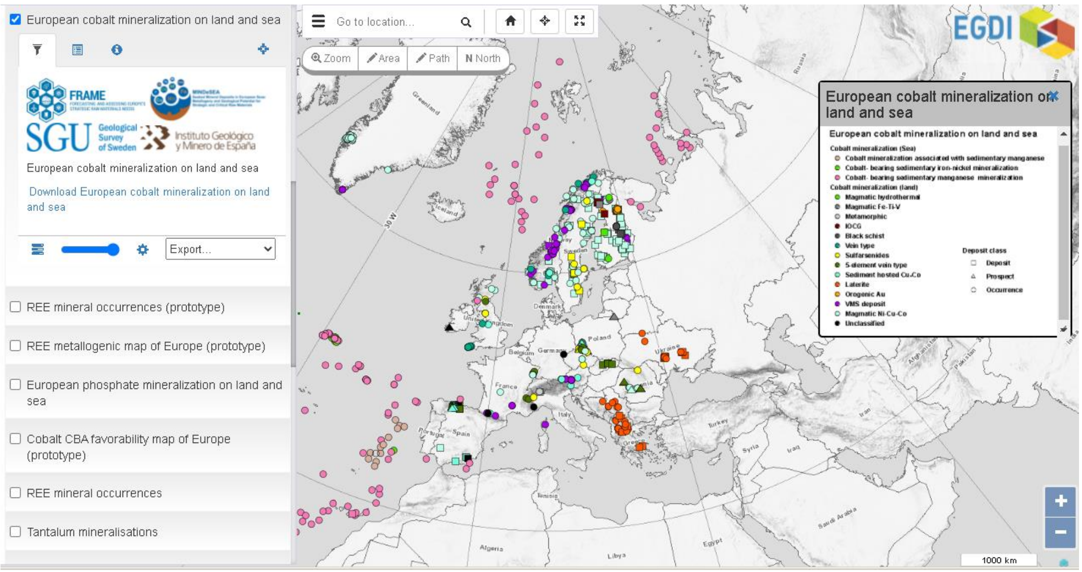

Figure A – European Cobalt mineralization on land and sea (MINDeSEA project) interactive map. Source: EGDI (geus.dk).

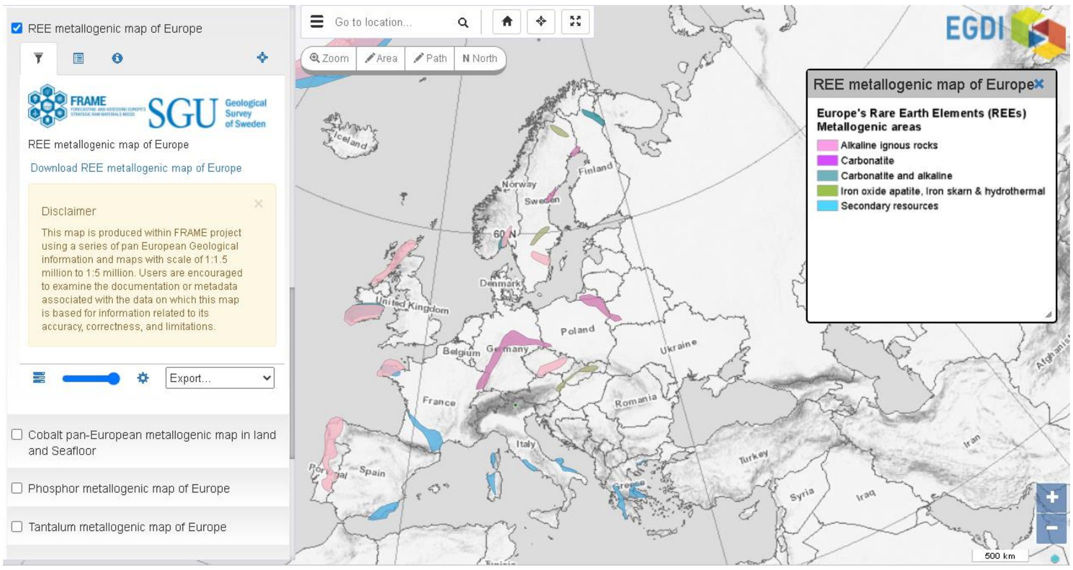

Figure B – REE metallogenic interactive map of Europe. Source: EGDI (geus.dk).

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GeoERA RAW MATERIALS

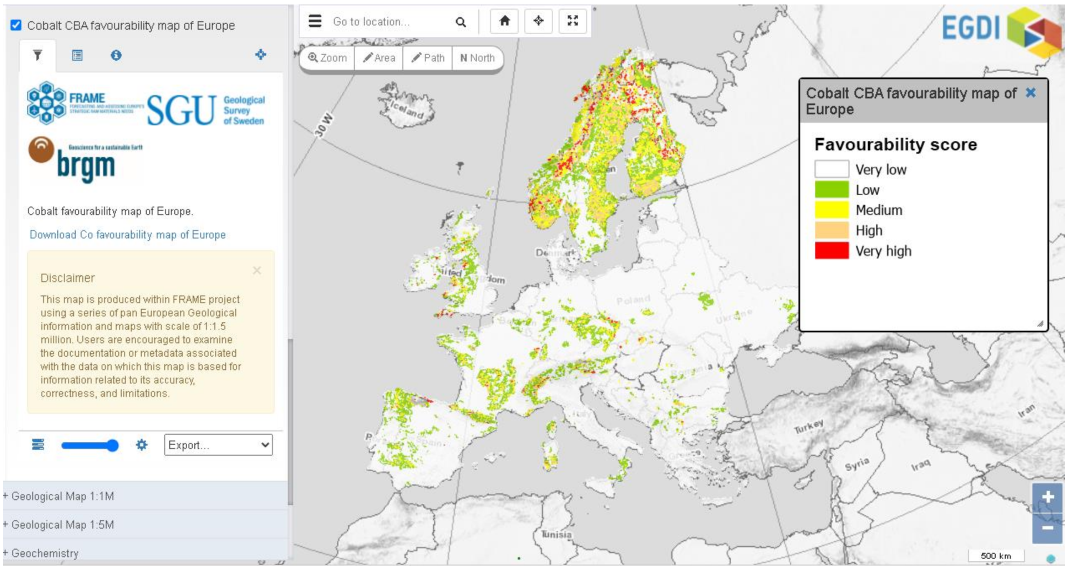

Figure C – Cobalt CBA favourability interactive map of Europe. Source: EGDI (geus.dk).

Unstructured data are available in EGDI Repository Search Platform with an example given in Figure D.

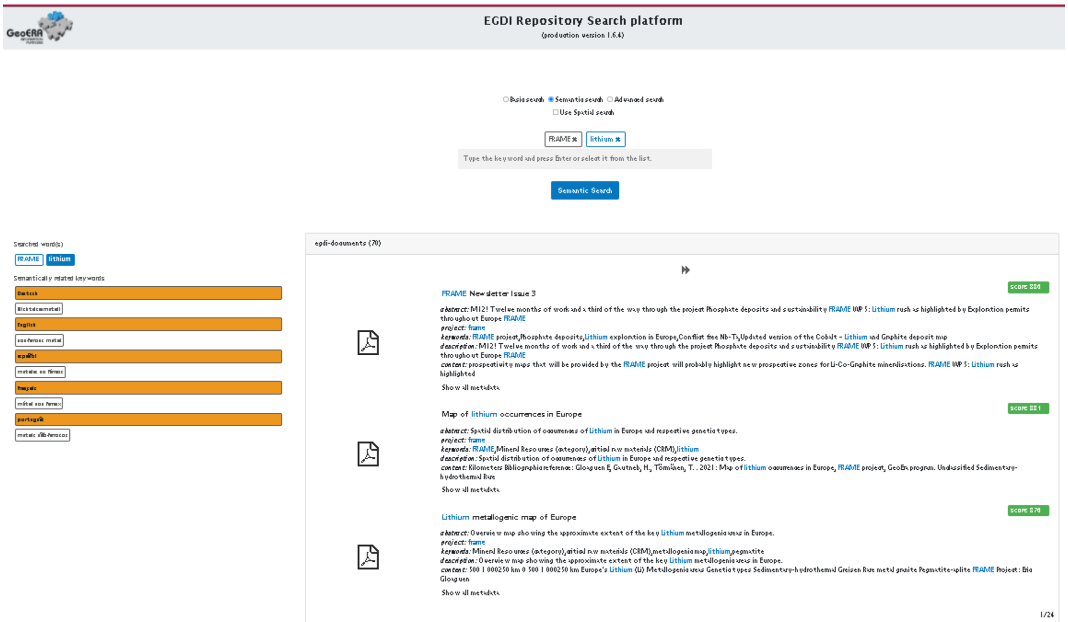

Figure D – Example of a semantic search for the keywords "lithium" and "FRAME" in the EGDI Repository Search Platform.

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FRAME - Forecasting and Assessing Europe's Strategic Raw Materials Needs

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