FRAME

FORECASTING AND ASSESSING EUROPE'S
STRATEGIC RAW MATERIALS NEEDS

DELIVERABLE D3.5

Prospectivity maps of critical raw materials in Europe

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166

GeoERA
RAW MATERIALS

FRAME

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Executive summary

The present report describes the mineral prospectivity maps that were produced by the work package (WP) 3 of the FRAME project. These prospectivity maps assess the favourability in Europe, at continantal scale, for lithium, cobalt, natural graphite, phosphate, niobium, tantalum and rare earth elements. They are based on datasets produced by the FRAME project (WP4 for phosphate, WP5 for lithium, cobalt and graphite, and WP6 for niobium and tantalum) and by the former EURARE project for rare earth elements.

Favourability scores were calculated with the CBA (Cell Based Association; *Tourlière et al., 2015*) data-driven method that was developped especially for mineral prospectivity mapping at regional and continental scale, and with the 1 to 1.5 M geological map of Europe (*Billa et al., 2008*). The CBA method was improved during this work. These improvements include i) the addition of buffers around known deposits to identify lithological associations they are related too, and ii) a statistical testing and evaluation of several favourability scoring methods, in order to identify and select the most performant one for each dataset.

The main outputs of this work are the prospectivity maps at european scale for lithium, cobalt, natural graphite, phosphate, niobium, tantalum and rare earth elements presented hereabove. These maps are important tools to help assessing the favourability and potential for critical raw materials primary resources across Europe. In that sense, they constitute a significant step towards a better understanding and assessment of the primary raw material potential in Europe. They highlight areas that are known for their geological potential for CRM in Europe, such as the Variscan and Alpine belts for lithium, for instance, but more importantly, they identify areas were no or few deposits are known. These underexplored areas might deserve closer attention to better assess their favourability and potential. In that sense, further developments of this work could be detailed metallogenic evaluation of the favourability results, and more focused prospectivity mapping, at regional scale for instance, of the most prospective areas, including diversified sources of data (such as geology, tectonic structures, geophysics, geochemistry, etc.).

One should keep in mind however that these prospectivity maps are based solely on geological information and that they are a first order assessments at continental scale.

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The reason is that the geological map is the only data source that is exhaustively and homogeneously covering the whole european continent. Consequently, they are first order assessments of the geological favourability for the commodities in scope, without any economical consideration. Still, they constitute a critical source of information, for public authorities policy making, or to help target future exploration areas, for instance.

In addition, a test of combined data-driven and expert-guided mineral prospectivity mapping at contiental scale has been conducted, using a hybrid fuzzy weight of evidence approach. This test allowed i) to test an additional method for mineral prospectivity mapping at continental scale, and ii) to compare both CBA and hybrid fuzzy WofE methods and to ssess their respective strengths and weaknesses.

The seven CBA prospectivity maps presented and described in this report are freely accessible as information layers and downlodable as pdf documents in the online EGDI data platform. As a consequence, they will remain available and visible to all end users beyond the lifetime of the FRAME project.

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1 Introduction

The prime objective of work package (WP) 3 in the FRAME project was to produce maps of strategic and critical raw materials (SCRM) in Europe, including the so-called energy and conflict minerals. In cooperation with other FRAME WPs, there was a consensus on the methodology used for the identification and selection process of the SCRM to be included in the metallogenic map (*Arvanitidis, et al., 2019*), linked mainly to information collected from existing databases, such as the ones of ProMine, Mineral4EU (M4EU) and European Geological Data Infrastructure (EGDI).

EuroGeosurveys Mineral Resources Expert Group (MREG) presented an updated map on critical raw materials in 2017, (Figure 1; *Bertrand et al., 2018*), based on the ProMine mineral deposit database. The mineral resource information, including data sharing and networking by European Geological Surveys, is crucial and the main focus on WP3 in FRAME project is to update the CRM and strategic raw materials and also to introduce pan European metallogenetic belts on selected commodities, including Energy and conflict minerals.

In this report we present an overview of the maps of main metallogenic provinces in Erope presented in D3.3 of the FRAME project for rare earth elements, graphite, cobalt, lithium, phosphates, niobium and tantalum. These maps were compiled with datasets produced by and in collaboration with other work packages (WP4, WP5 and WP6) of the FRAME project and with the Mineral Resource Expert Group (MREG) of EuroGeoSurveys. We compare these maps with prospectivity maps produced using cell-based association (CBA) method (*Tourlière et al., 2015*), in order to assess the favourability of known prospective areas and hopefully identify new ones. The Methodology and and prospectivity maps of all commodities in scope are presented in detail in the present report.

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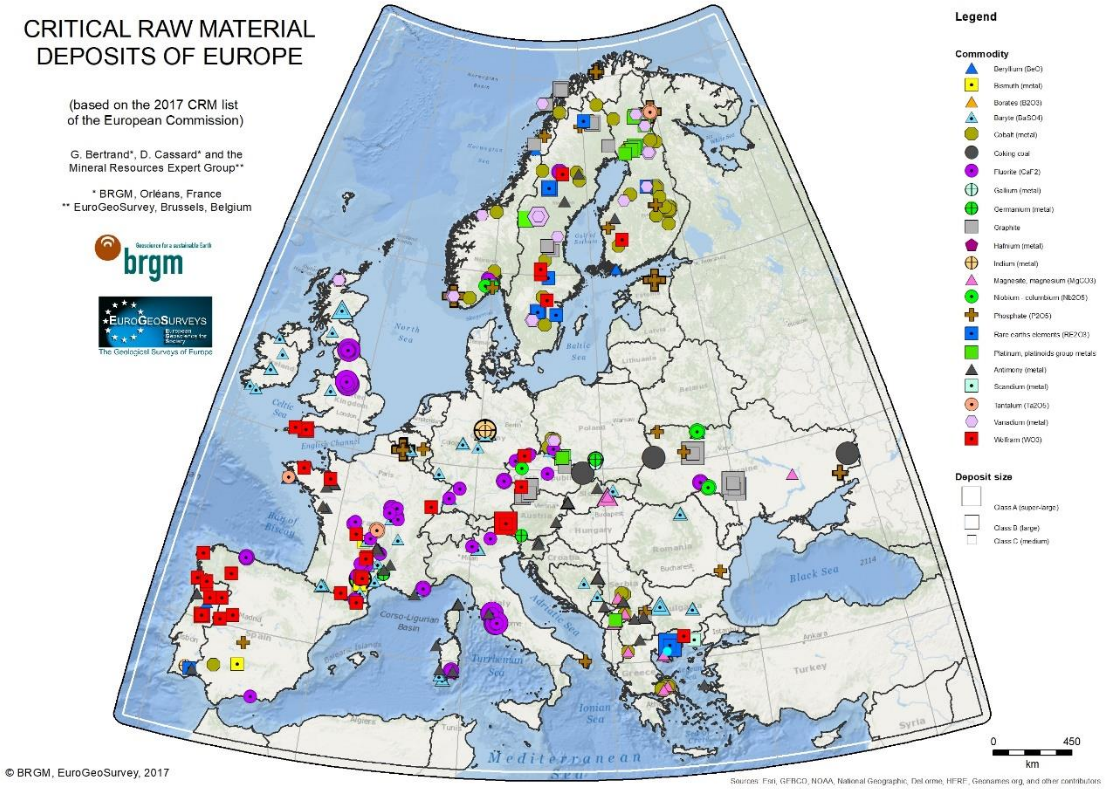

Figure 1- An overview of main Critical Raw Material (CRM) deposits (Bertrand et al., 2018)

2 Mineral prospectivity mapping

In the past, economic geologists used a light table to simply overlay different thematic maps to examine spatial relationships and analogue data integration between important multi-disciplinary criteria to guide exploration and produce mineral potential and other relevant maps. Nowadays, it is possible to collect and store the data and information in digital formats and to use different GIS and statistical approaches to deliver maps showing favourable areas referring to a specific commodity. *Carranza (2017)* describes mineral potential mapping (MPM- also termed mineral potential modelling) as quantifying and mapping of the likelihood that mineral deposits may be found by exploration in a study area.

An objective of workpackage (WP) 3 in the FRAME project is to produce predictive assessments – in the form of prospectivity maps (predictivity maps) - of CRM based on

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GIS exploration tools at the continental scale, in order to identify high potential mineral provinces and mining districts.

The basic purpose of prospectivity mapping is to assess the spatial distribution of the favorability of occurrence of a non-random phenomenon (assuming that a phenomenon cannot be predicted if it is purely random). In the case of mineral prospectivity mapping, the phenomenon is the occurrence of a mineralization. A large number of mineral prospectivity mapping methods exist. They can be grouped in two categories:

- The “expert guided” methods rely on the existing knowledge of experts, in the form of e.g., exploration guides or metallotects. These guides are searched to discover analogs and hopefully new mineralization. This is more or less how mineral exploration was empirically conducted by economic geologists in the past centuries. The development of computers and databases during the last decades allowed to automatically process larger volumes of data and thus improve the accuracy and reliability of the methods;
- The “data driven” methods rely more on the processing of data to deduce “knowledge” (“learning” from input datasets) that is then used to identify the areas that are favourable to discover new mineralization. Date driven methods largely progressed in the past decades with the tremendous development of computing capacities and databases.

When it comes to mineral prospectivity mapping at continental scale (which is the goal of this work), encompassing huge geographic coverage, numerous geological environments and large volumes of data, data driven methods are well appropriate. In this work, we have used a data driven approach – the CBA (for Cell Based Association) – that has been recently developed by BRGM (*Tourlière et al., 2015*). Preliminary results on prospectivity mapping are presented and published in different events (e.g. *Bertrand et al., 2020, Sadeghi et al., 2020a and Sadeghi et al., 2020b*)

2.1 The Cell Based Association method

2.1.1 Common issues in mineral prospectivity mapping

Most data driven mineral prospectivity mapping methods are based on unequivocal relationships between points (e.g., known deposits) and the cartographic entities that contain them (pixels or polygons associated with, for instance, geological information).

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The knowledge "learned" by the process will be solely based on this unequivocal relationship. For instance, a deposit will unequivocally be linked to the lithology polygons that contains it, without considering surrounding lithologies. This "shortcut" may lead to several issues that could significantly bias the results.

The first issue resides in the uncertainties in polygon contours and point location. Cartographic objects are drawn with a certain error in their location that could be significant, especially at continental scale. That may result in a wrong association between a point (deposit) and a polygon (lithology). In addition, geological maps display surficial formation that could cover large areas but are not related to mineralization (Quaternary covers, for instance).

The second issue resides in the fact that the surface of polygons are often considered a relevant parameter for weighting. That is the case for instance in the Weight of Evidence method (*Bonham-Carter et al., 1988, 1989; Agterberg et al., 1990*) where surfaces of lithological formations are used to calculate density of deposits. This may lead to artefacts because geology is in 3D and the surface extension of a formation is not necessarily related to its overall importance.

The third issue resides in the spatial distribution of points that is often not considered in data driven mineral prospectivity methods. That may lead to the inappropriate generalization of a local feature to a whole formation. For instance, skarn deposits are not located in a whole carbonate formation, but along its contact with intruding magmatic bodies.

To solve these issues, we believe that considering the geological environment around known deposits and "learn" from this information to assess the favorability is more appropriate than considering solely the "point-polygon" unequivocal link. The CBA method has been developed with this underlying base principle.

2.1.2 Overview of the CBA method

The application of the CBA method relies on a succession of relatively simple steps of data processing and calculation. The basic needs in terms of data to apply the method are 1) a set of known deposits containing the targeted commodity in the area of study (learning set) and 2) a map of relevant geological features. In the present study, we have used datasets of deposits produced by work packages 4, 5 (*Gautneb et al., 2020*) and 6

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(*Reginiussen et al., 2021*) of the FRAME project, by the the EURARE project for rare earth elements, and the 1 to 1.5 million geological map of Europe compiled by BRGM (*Billa et al., 2008*).

The first step of the CBA method is to superimpose a regular grid ("cells") over the area of study (Figure 2). The size of the cells is an important parameter that is directly connected to the scale of the input map. If they are too small, most of them will intersect only one lithology polygon, if they are too large, they will intersect "too many" (if not all) lithology polygons. The cell size needs to be carefully chosen to allow sufficient lithological association variability in all the cells.

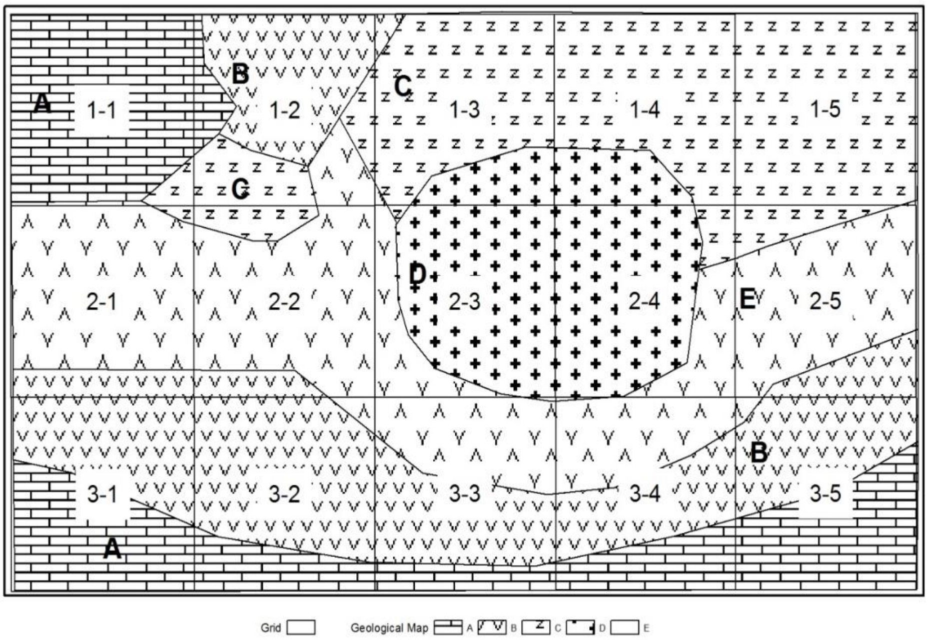

Figure 2 - The first step of the CBA method is to superimpose a regular grid over the area of study.

In the second step, an attribute table is built from the intersection between the grid and the map polygons. This attribute table codes the presence (1) or absence (0) of each lithology in each cell of the grid. It then provides a "lithological spectrum" that describes the lithological associations in all cells of the grid. Note that the surface of the intersection between lithological polygons and cells is not considered, owing to the fact that it is likely meaningless in 2D (as geology is 3D).

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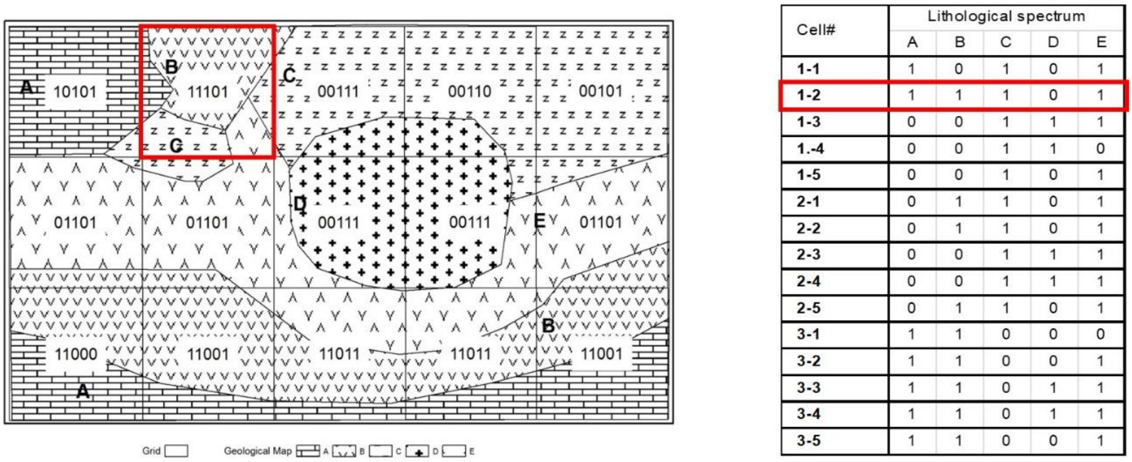

Cell#	Lithological spectrum				
	A	B	C	D	E
1-1	1	0	1	0	1
1-2	1	1	1	0	1
1-3	0	0	1	1	1
1.-4	0	0	1	1	0
1-5	0	0	1	0	1
2-1	0	1	1	0	1
2-2	0	1	1	0	1
2-3	0	0	1	1	1
2-4	0	0	1	1	1
2-5	0	1	1	0	1
3-1	1	1	0	0	0
3-2	1	1	0	0	1
3-3	1	1	0	1	1
3-4	1	1	0	1	1
3-5	1	1	0	0	1

Figure 3 - Each cell of the grid (left) is coded in an attribute table (right) for the presence (1) or absence (0) of each lithology.

In a third step, we identify the lithological associations related to known deposits. To do so, a buffer is drawn around each deposit, which surface is equal to those of cells. Lithological associations in all buffers are coded similarly to grid cells. At the end of this process, we have built two attribute tables to describe lithological associations: one for the cells of the grid and one for the buffers around known deposits. The lithological associations in buffers are associated with deposits and are then considered favourable (Figure 3). The following step is to compare lithological associations of grid cells and buffers. A simple way is to consider as favourable all associations in grid cells that are exactly similar to favourable associations in deposit buffers. For instance, in Figure 4, the two green cells in the upper middle of the figure could be considered favourable because they have exactly the same association found in deposit 2 buffer. Another way to compare lithological associations in grid cells and buffers is to group them, using algorithms such as AHC (ascending hierarchical classification). A third way is to score all cells of the grid on their similarity with favourable associations in the buffers. This last yields a continuous range of values for all cells of the grid, allowing a more precise assessment of their relative favourability.

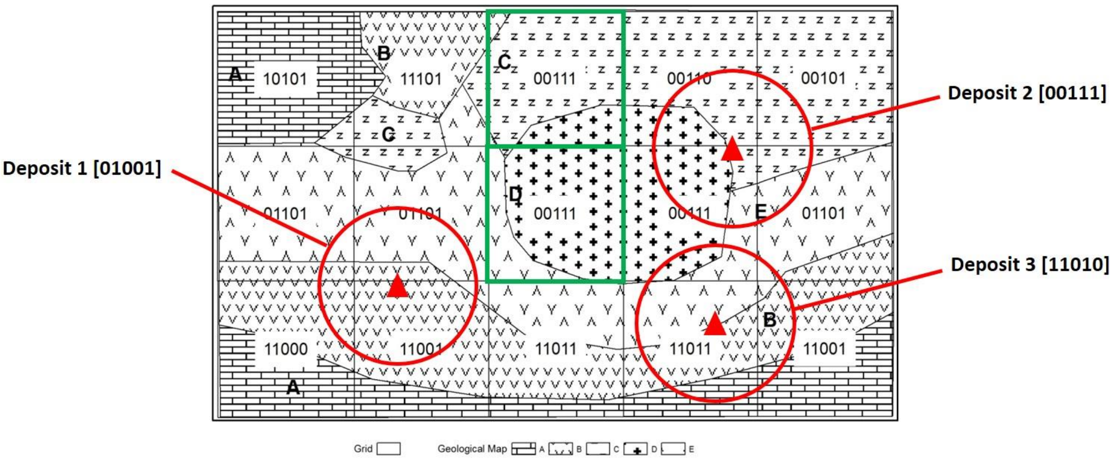

Figure 4 - Lithological associations in cells and deposit buffers are compared to identify favourable cells.

2.2 Statistical optimization of favourability scores

In the present work, we have chosen to score (rank) all the cells of the grid on the similarity of their lithological associations with those contained in the deposit buffers. To do so, we use a frequency ratio (FR) that is calculated according to the following formula:

$$FR = \frac{\text{frequency of lithology n in all deposit buffers}}{\text{frequency of lithology n in all cells of the grid}}$$

FR shows if a lithology is preferably associated with known deposits (FR>1) or not (FR≤1).

There are certainly many ways to combine frequency ratios to calculate the score of each cell. In this work, we have tested five of them that are:

- The sum of FR of all lithologies present in the cell;
- The product of FR of all lithologies present in the cell;
- The sum of « favourable » lithologies (FR>1) present in the cell;
- The product of « favourable » lithologies (FR>1) present in the cell;
- The simple sum of the frequency in deposit buffers of all lithologies present in the cell.

For each commodity (i.e. dataset, see Chapter 3 below) in the scope of the project, these five scoring approaches were statistically tested, in order to assess their performance and identify the most accurate. To do so, we performed the followings tasks for each dataset:

- 100 CBA prospectivity test maps were calculated;

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- For each one of them, 50% of the dataset (randomly selected) was used as training set and the remaining 50% was used as controlling set;
- For each test map, a ROC (Receiver Operating characteristic) curve was calculated with the controlling set and its performance was measured with the AUC (Area Under Curve) indicator;
- For each scoring method, an average AUC value and standard deviation were calculated, that allowed to measure its performance per dataset.

For each of the 7 datasets (Li, Co, graphite, Nb, Ta, phosphate and REE), scoring methods were evaluated on their average AUC value. The results of these statistical tests, summarized in Table 1 and in the bar diagram of Figure 5, yield some interesting information that can be synthetized in the following points:

- Performances were not even in all datasets; they were signifanctly higher for natural graphite and tantalum, with best averaged AUC values of approx. 0.9, while they were significantly lower for phosphate and REE, with best averaged AUC values of approx. 0.74; Number of deposits in datasets does not seem to be correlated with their performance: the tantalum dataset, for instance, produced the highest averaged AUC value (0.90) with only 162 deposits, far less than the cobalt dataset that produced a lower best averaged AUC value of 0.85 with 526 deposits.
- For all datasets, the "simple product of FR" scoring method always significantly underperformed; the reason for the lower accuracy of this scoring method is not clear yet, but we believe it may be partly explained by the possibly high volatility of multiplying frequency ratios when some are very high and/or very low;
- For all datasets, the "simple sum of frequencies in deposits" scoring method always slightly underperformed; this highlight the fact that frequency ratios (FR) are appropriate to score the favorability of cells;
- For all datasets, the "simple sum of FR", the "sum of favourable (>1) FR" and the "product of favourable (>1) FR" scoring methods provided relatively similar results; depending on datasets, one or another provided slightly better results; for cobalt, lithium and natural graphite, the best averaged AUC values were obtained with the "simple sum of FR"; for phosphate and REE, the best results were obtained with the "sum of favourable (>1) FR", and with the "product of favourable (>1) FR" for niobium and tantalum; in any case, all these three scoring methods seem appropriate for scoring CBA cells.

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The main result of these statistical test was to use the most performant scoring technique for each dataset and each prospectivity map, i.e. “simple sum of FR” for cobalt, lithium and graphite, “sum of favourable (>1) FR” for phosphate and REE, and “product of favourable (>1) FR” for niobium and tantalum.

Scoring method	**Cobalt**	**Lithium**	**Natural graphite**	**Niobium**	**Phosphate**	**Rare earth elements**	**Tantalum**
Simple sum of FR	0.8488	0.86096	0.8969	0.85273	0.73986	0.72539	0.89895
Sum of FR greater than 1	0.84486	0.85739	0.89375	0.85311	0.74499	0.73881	0.89972
Simple product of FR	0.7714	0.78701	0.83131	0.73748	0.64484	0.61089	0.82167
Product of FR greater than 1	0.83998	0.85649	0.89355	0.85649	0.73828	0.73358	0.90078
Simple sum of frequencies in deposits	0.79709	0.8306	0.85295	0.83294	0.71606	0.65201	0.89112

Table 1 - Averaged AUC score per dataset and scoring method; cells in green contain the best averaged AUC score for each dataset.

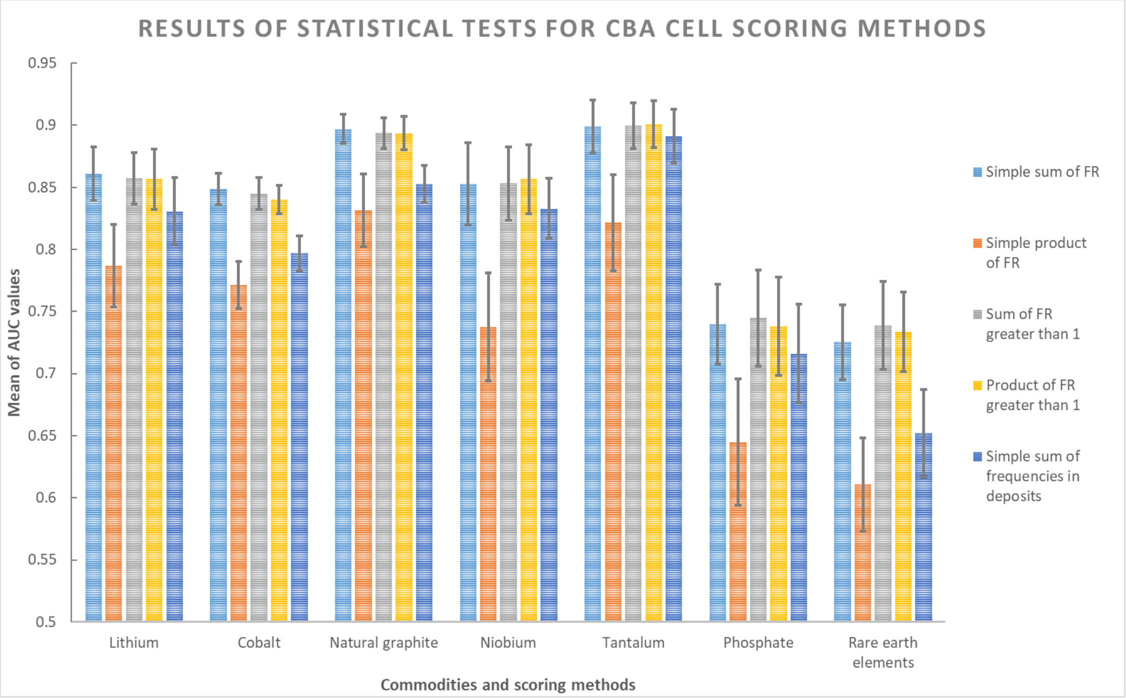

Figure 5 - Results of the statistical tests of CBA cell scoring methods for the Li, Co, graphite, phosphate, Nb, Ta and REE datasets.

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3 Prospectivity mapping of CRM in Europe

3.1 Input datasets

The CBA prospectivity maps were calculated with the deposit datasets compiled by WP 4 (phosphate), 5 (lithium, cobalt and natural graphite; *Gautneb et al., 2020*) and 6 (niobium and tantalum, *Reginiussen et al., 2021*) of the FRAME project and by the EURARE project for rare earth elements. Datasets produced by WP 4, 5 and 6 were further queried and processed to isolate relevant deposits and produce seven datasets, one for each commodity in scope: lithium, cobalt, natural graphite, niobium, tantalum, phosphate and rare earth elements. The number of deposits per dataset was 595 for Li, 526 for Co, 509 for graphite, 162 for Nb, 162 for Ta, 85 for phosphate and 168 for REE (Figure 6).

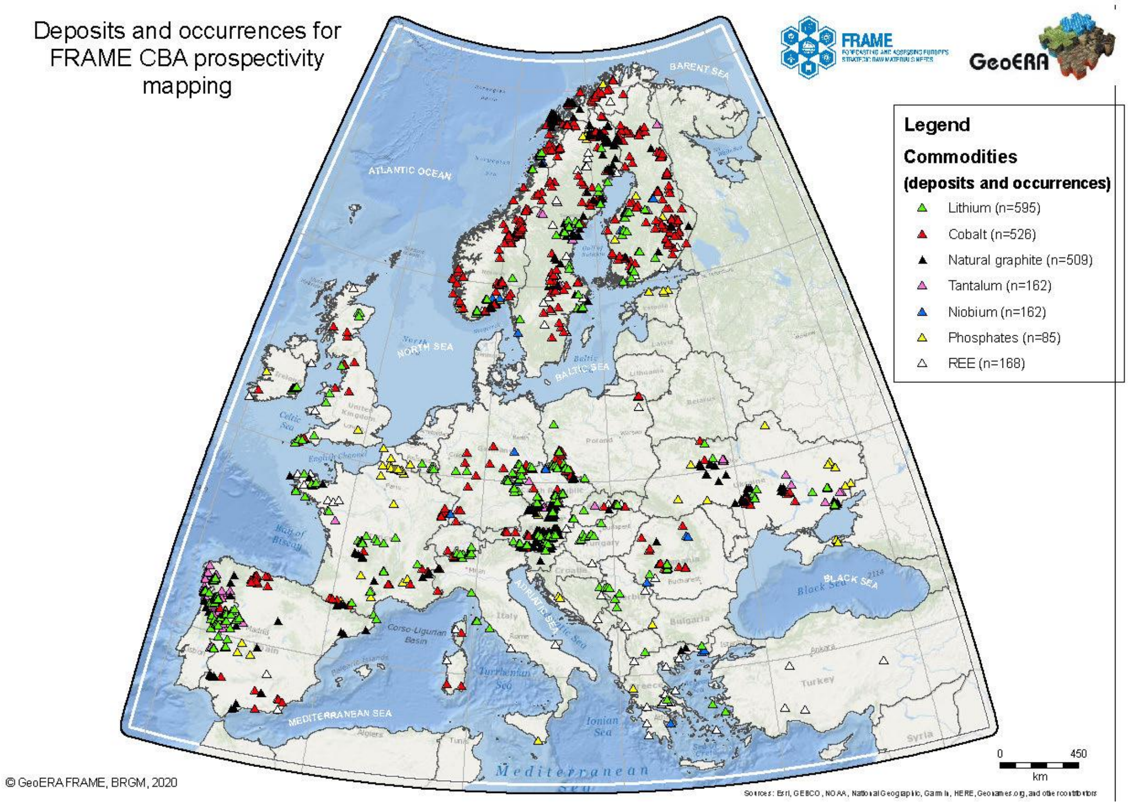

Figure 6 - Distribution of deposits from the datasets used to produce the CBA prospectivity maps.

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The CBA prospectivity maps are also based on the 1 to 1.5 million geological map (1/1,500,000) compiled by BRGM (*Billa et al., 2008*) and a regular grid of 10 by 10 km cell size. 10 by 10 km may seem rather coarse, and it certainly is, but it is in the order of size of an exploration permit, and it was a good compromise between "geological reality" and "computing constrains". Note that the CBA prospectivity maps do not include Greenland, although it is a highly strategic region for mineral exploration. The reason is that the input 1 to 1.5 million geological map of Europe does not cover Greenland. However, the fuzzy weight of evidence approache, in the present work, uses different data sources and includes Greenland.

To ease the reading of the prospectivity maps, favourability scores have been color coded in five classes, going from "very low" to "very high" favorability. Note that it is a relative classification. Note also that the visual result significantly depends on the method used to classify the scores.

Finally, note that only the geology (lithology) was used to characterize the associations in grid cells and deposit buffers. No geochemical or geophysical datasets were used because no such dataset was available at the scale of the whole European continent. Anyway, further developments of the present work could be done to refine the CBA prospectivity mapping at regional scale, in favourable areas, with additional pertinent datasets.

3.2 Lithium

3.2.1 Main mineral provinces for lithium in Europe

Based on the distribution of lithium deposits and occurrences, deliverable D3.3 of the FRAME project (*Sadeghi et al., 2020*) identified 25 metallogenic provinces (Figure 7). Magmatic and magmatic-hydrothermal lithium mineralization form numerous provinces that are mainly associated the Svecofennian and the Variscan orogenies. Sedimentary-hydrothermal provinces are hosted in more recent terranes (Cambrian to Neogene): 1) in some area (Li-bearing Fe-Mn deposits) of the Palaeozoic and Mesozoic sedimentary platforms affected by fluid circulation; 2) in the Neogene accretionary belts that are affected by extensional tectonic setting and arid climate during the Miocene (e.g. Jadar deposit, Pannonian basin); 3) in Mesozoic-Paleogene bauxites developed on the Pelagonian metamorphic massif (e.g. Hungary, Greece).

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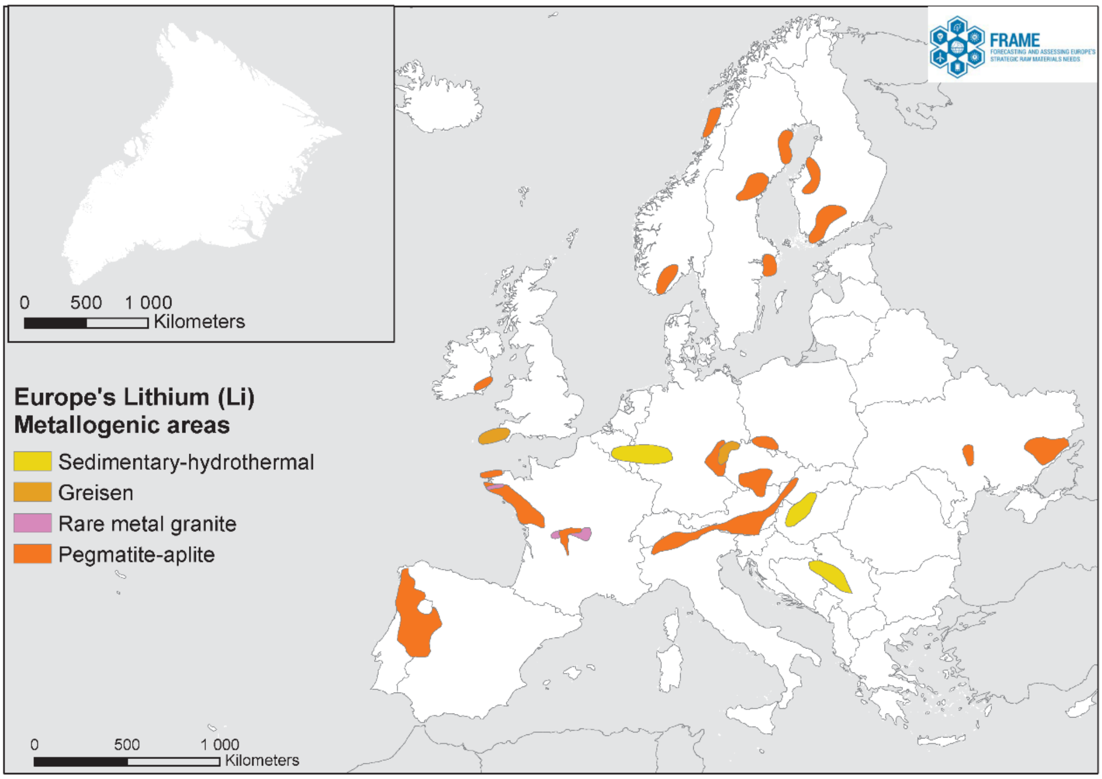

Figure 7 - Main metallogenic provinces for lithium in Europe and their genetic types (Sadeghi et al., 2020).

Numerous Li-rich pegmatites are observed in several pegmatites field throughout Europe. Several fields of spodumene and petalite-bearing pegmatites are known in the Archean basement, in the Shpolyansko-Tashlykskiy and Shevchenkivske provinces in central and eastern Ukraine, respectively. In Finland and Sweden, prospective lithium-rich pegmatites are associated to the Svecofennian orogen (1.92-1.77 Ga). Most of them are emplaced close to dome or dome-like migmatitic areas affecting metasedimentary belts. Migmatitic areas are also intruded by numerous anatectic granites. Some typical examples are the Kaustinen or the Somero-Tammela provinces in southern Finland. To the west in central Sweden, the Bothnian basin made of sedimentary and volcanic rocks (1.91-1.86 Ga) hosts the Skellefteå and Västernorrland provinces. In southern Sweden, the Stockholm province host the smallest potential.

Another very prospective target is represented by Variscan pegmatites. The most important Variscan lithium-bearing pegmatite areas are the Galicia – Central-Iberian province (Portugal and Spain), composed of more than 20 major Li-pegmatite deposits,

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and the Almendra-Fregeneda pegmatite field at the Spain-Portugal boundary. In France, the most prospective areas for pegmatites are the Ambazac-Creuse-Millevaches province (western Central Massif), the South Brittany province and the Leon province (northern Brittany). In the Bohemian Massif, lithium-bearing pegmatite fields are mainly represented by the Sudetes, the Saxo-Thuringian and the Moldanubian provinces. In United Kingdom, the main Lithium-rich pegmatite-aplite is the Meldon aplite located in the Cornwall province. In Romania, Spodumene-albite subtype pegmatites are known in the Conţu-Negovanu pegmatite field (South Carpathians). In Austria, pegmatites are not Variscan but Lower Permian in age. The Austroalpine province is composed of many pegmatites in an area stretching approx. 400 km from the north of Torino to the south of Vienna.

Lithium-rich high-phosphorus rare element granites are scarce in Europe. Despite their small size (<1 km3) they are hosting large disseminated mineralization. Some amblygonite-quartz veins could be associated with those granites. In France, the most important target for lithium-rich granites is the rare element belt that includes several rare-element granites and rhyolite. To the west, in the Armorican massif, the Audierne bay province includes several dykes of Li-rich high-phosphorus rare element granite. In Spain and Portugal, several isolated amblygonite-quartz veins, amblygonite-lepidolite-bearing rare-element granite are also known in the central Iberian zone. In the United Kingdom, the Saint Austell granite contains a large volume of disseminated Li-bearing micas (Zinnwaldite, Lepidolite).

The most important lithium-rich greisens are located within lithium-poor low-phosphorous rare element granites in the Erzgebirge province at the Czech-Germany boundary. Numerous greisens are known in this area, the most emblematic of which being the Cinovec and Zinwald greisens. In the United Kingdom, main greisen mineralization are located in the Cornwall province. The Tregonning-Godolphin and Cligga-Head granites represent small but significant volumes of metasomatised granite with lithium hosted by lepidolite.

Some European mineralization are related to exogenous processes (fluid circulation, supergene weathering, alterite remobilization by erosion, etc). Among the various type of lithium mineralization associated to these processes, the main known lithium mineralization in Europe are the Jadar-type, some Li-bearing Mn-Fe- mineralization (lithiophorite) and some Li-bearing bauxites. Li-rich hectorite mineralization seems to be

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absent in Europe. In Serbia, the Jadar deposit is the most important deposit of the Jadar province. In Europe, bauxite deposits occur from Spain to Turkey, including parts of southern France, Hungary, Italy, Greece and the Balkans. Despite this large number of occurrences, the lithium content of European bauxite remains poorly constrained apart from the West Hungary bauxite province.

In Europe, Lithiophorite-bearing Fe-Mn deposits are of 2 types: Fe-Mn reddish siliciclastic rocks and Mn-Fe lenses or layers. In these Fe-Mn rich rocks, the presence of lithioporite is secondary, related to fluid circulation. Despite the presence of lithiophorite, the amount of lithium is generally low. A first group of deposits in Scotland, Wales, England and in the Ardennes province is Cambrian to Early Ordovician in age. The second group is mainly found in Hungary with deposits of Jurassic age.

3.2.2 CBA prospectivity map for lithium

As for all other commodities in the scope of this work, the CBA prospectivity map for lithium (Figure 8) includes deposits of various types (pegmatites, greisens, rare metal granites, etc.) and therefore highlights areas that are favorable not for a specific type but for lithium-bearing mineralization in general, no matter its type.

The prospectivity map does not mimic the map of main metallogenic provinces for lithium in Europe (Figure nnn). For instance, it does not highlight the pegmatite-aplite metallogenic areas in Norway, Ukraine and Ireland, neither does it show the sedimentary-hydrothermal area in the Pannonian basin. It shows with medium favourability the pegmatite-aplite areas in eastern Sweden and southwestern Finland but significantly enlarge their geographic extension, which suggests that favourable geological contexts span over much larger areas.

The prospectivity map clearly highlights the lithium metallogenic areas in the variscan and alpine belts (Sapin-Portugal-France-Central Europe and northern Italy-Austria, respectively) with high to very high favourability, but here again, it significantly enlarges their geographic coverage. For instance, the prospective areas in Iberia also includes Alentejo in Portugal, or Galicia, Extremadura and western Castilla-La Mancha in Spain. Similarly, it includes most of the Central Massif in France and the Pyrenees along the Spanish-French border.

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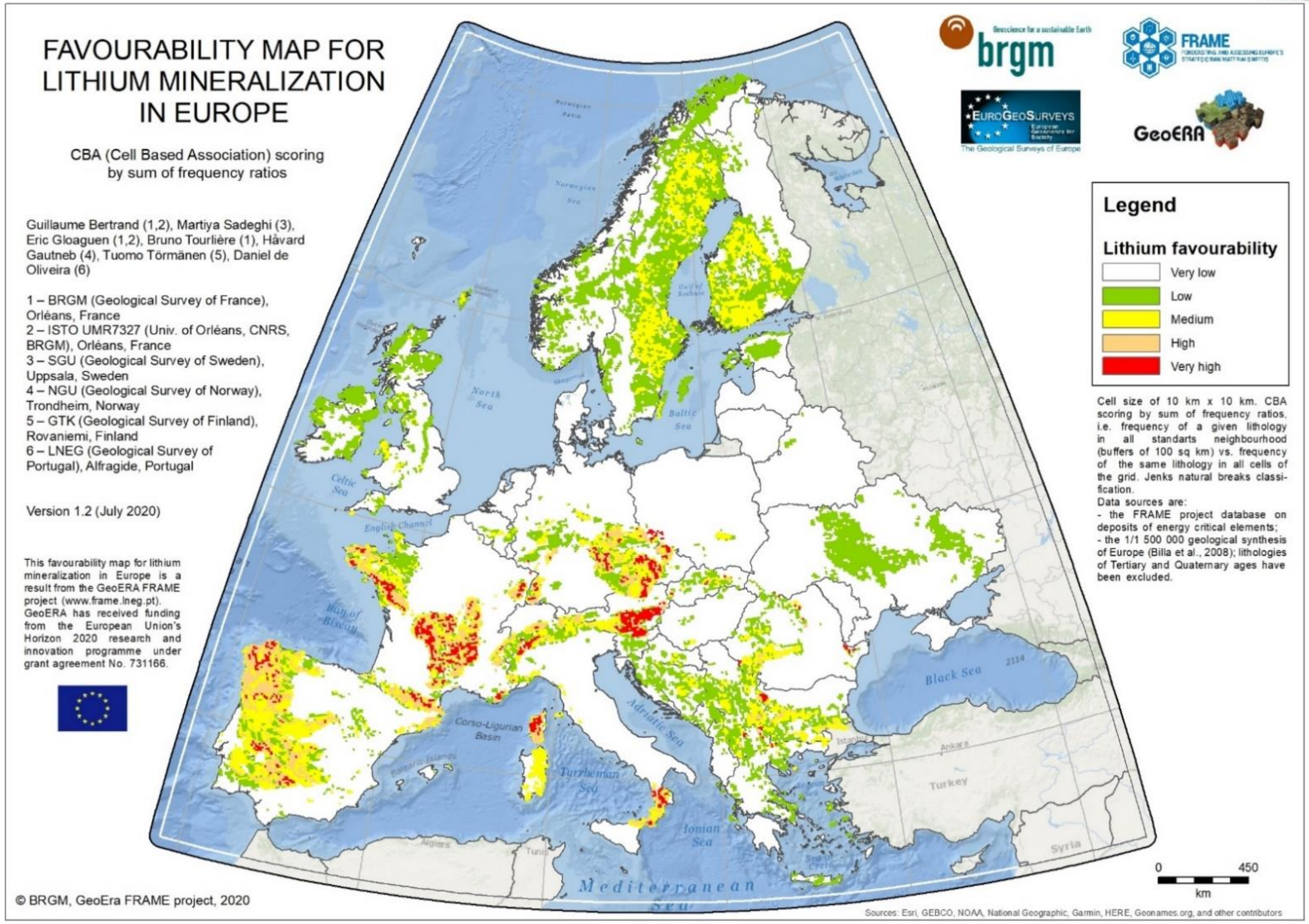
In addition, several highly prospective areas are not identified in Figure 7 as metallogenic areas. These are for instance the Vosges and Schwartzwald mountains along the French-German border, or a large region in the southeastern Europe Alpine domain, spanning over Balkan countries, western Bulgaria and southwestern Romania. Similarly, very high prospectivity areas are highlighted in Corsica and in metamorphic and intrusive series in Calabria, southern Italy. These areas contain geological contexts that are favourable for lithium mineralization. As such, they should be checked to test whether their high favourability is geologicaly significant and they would deserve further interest and studies to refine their potential.



FAVOURABILITY MAP FOR LITHIUM MINERALIZATION IN EUROPE

CBA (Cell Based Association) scoring by sum of frequency ratios

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4 – NGU (Geological Survey of Norway), Trondheim, Norway
5 – GTK (Geological Survey of Finland), Rovaniemi, Finland
6 – LNEG (Geological Survey of Portugal), Alfragide, Portugal

Version 1.2 (July 2020)

This favourability map for lithium mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Cell size of 10 km x 10 km. CBA scoring by sum of frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification.

Data sources are:
- the FRAME project database on deposits of energy critical elements;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008); lithologies of Tertiary and Quaternary ages have been excluded.

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Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Figure 8 - CBA prospectivity map for lithium mineralization in Europe.

3.3 Cobalt

Main mineral provinces for cobalt in Europe

Cobalt occurs as relatively common trace to minor constituent in many deposit types of different commodities. In Europe, the most common deposit types are orthomagmatic Ni-Cu-Co, volcanogenic Cu-Zn-sulfide (VMS), Iron Oxide-Cu-Au (IOCG), 5-element and other vein-type deposits, sediment-hosted Cu, lateritic Ni-Co and metasediment-hosted Cu-Au-Co deposits (e.g. *Horn et al., 2020*). Generally, the Co content of these deposits vary from less than 100 ppm (0.01 %) to a few thousands of ppm. 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. Several lateritic deposits are clustered in the Balkans, Greece and Ukraine, but cobalt is generally not extracted from them. Currently cobalt extracted in Europe only comes from three mines in Finland.

As a minor constituent, cobalt is often not included in mineral resource and reserve estimates. Where available, data indicates significant resources, mainly in Finland, Norway and the Balkans. Largest resources occur in the black schist hosted Talvivaara (Sotkamo) Zn-Ni-Cu-Co mine in Finland and in the lateritic Mokra Gora Ni-Co deposit in Serbia (*Horn et al., 2020*)

Based on the clusters of occurrences, Sadeghi et al. (2020) identified 34 provinces (Figure 9). Broadly, the main cobalt metallogenic zones are the followings:

a) The Fennoscandian shield: Norway, Sweden and Finland
b) Greenland
c) The Balkans and Greece
d) SW and central Europe

Most of the cobalt occurrences of the Fennoscandian shield are Proterozoic in age, ranging from Archean to Early Proterozoic in Finland, Early Proterozoic in Sweden (Paleozoic in the Caledonides in westernmost Sweden) to Meso-Neoproterozoic to Paleozoic in Norway. All three countries contain a high number of identified Co-bearing occurrences (123 in Finland, 85 in Norway and 63 in Sweden). In Norway, most significant Co deposits are magmatic Ni-Cu-Co and Co-containing VMS deposits, essentialy in

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southern and central Norway. In Sweden, most of the known Co-deposits are magmatic Ni-Cu-Co mineralization in the Skellefte and Bergslagen areas.

The Balkan region and Greece host some 27 lateritic Ni-Co deposits and occurrences. Some deposit in Greece, Albania, Kosovo and North Macedonia have been mined for nickel but not for Co. However, they contain locally significant Co-resources, especially the Mokra Gora deposit in Serbia (*Horn et al., 2020*). Further lateritic Ni-Co deposits are described in Ukraine.

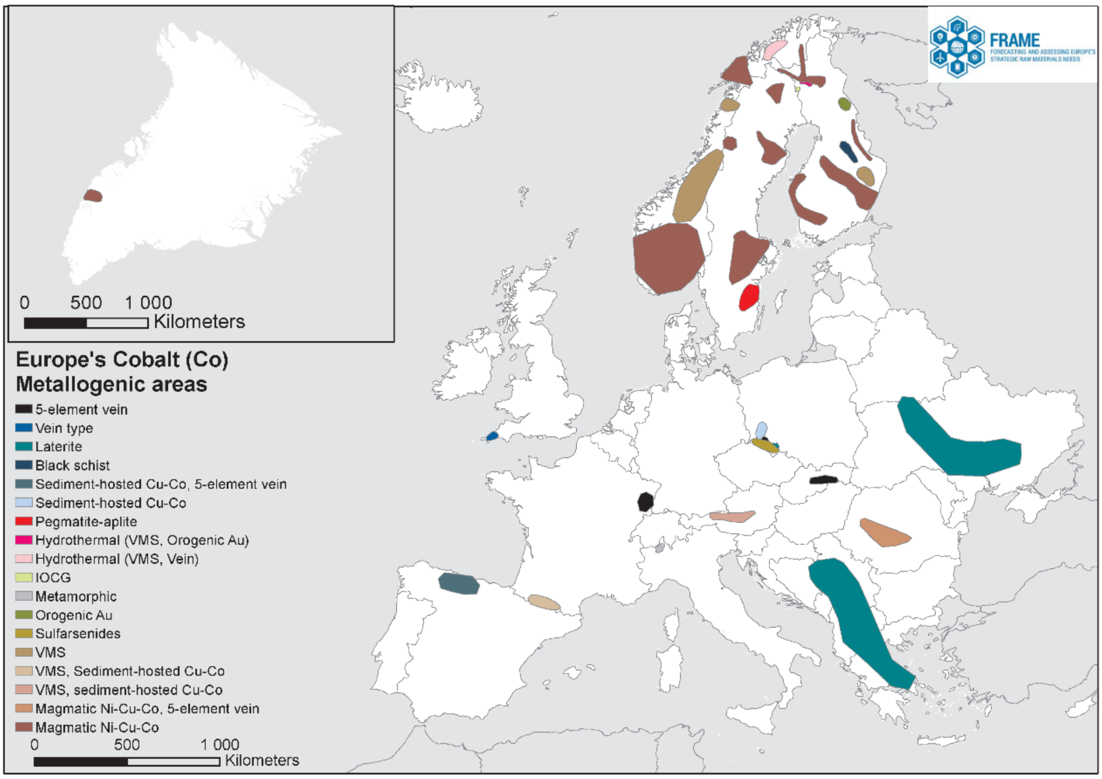


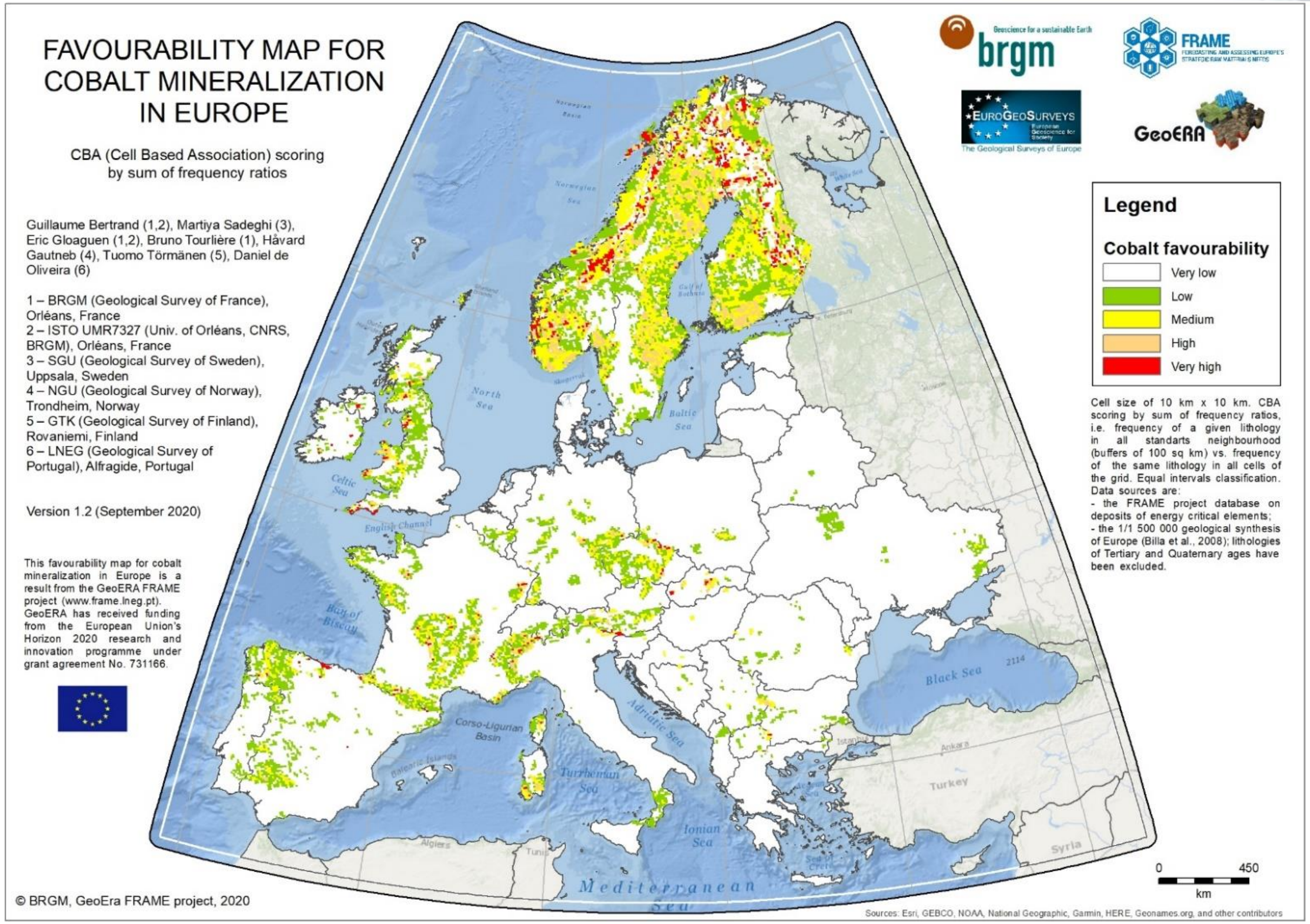
Figure 9 - Main metallogenic provinces for cobalt in Europe and their genetic types (Sadeghi et al., 2020).

Elsewhere in Europe, small and mostly historic Co deposits and occurrences are related to variscan and Alpine orogenies, extending from the Cantabrian Mountains in NW Spain, through Pyrenees, France, northern Italy, Austria, Slovakia and Romania to the east. A cluster of Co-deposits also occurs in SW Poland. They represent various deposit types, including sediment-hosted Cu-Co, 5-element veins, VMS (to SEDEX) and Co-sulfarsenide veins for the most important. In addition, magmatic Ni-Cu-Co deposits occur in Romania and lateritic Ni-Co deposits in SW Poland.

3.3.1 CBA prospectivity map for cobalt

The CBA map for cobalt (Figure 10) highlights the high favorability of the fennoscandian shield. Many of the cobalt deposits in the input dataset are located in this region. That partly explains the reason why it appears with such a high favourability. On the other hand, no or very few cobalt deposits in the dataset are located in eastern and southeastern Europe. That probably explains why large metallogenic areas in continental Greece, the Balkan region and central Ukraine are under-represented in the prospectivity map.

Still, a close study of favourability distribution reveals prospective areas that extend beyond the main cobalt metallogenic areas and that should be given more interest in future exploration works. In addition, the CBA prospectivity map highlights favorable areas where no or very few cobalt occurrences are known. That is the case for instance in the south of Galicia in northwestern Spain, in the Central Massif in France, in Northern Ireland and Wales in the UK, in western Slovakia, in northern- and southernmost Finland, and in various other areas. These favourable areas should be more thoroughly studied to check whether these high favourability scores are meaningfull in terms of metallogeic and geological contexts.



FAVOURABILITY MAP FOR
COBALT MINERALIZATION
IN EUROPE

CBA (Cell Based Association) scoring
by sum of frequency ratios

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5 – GTK (Geological Survey of Finland), Rovaniemi, Finland
6 – LNEG (Geological Survey of Portugal), Alfragide, Portugal

Version 1.2 (September 2020)

This favourability map for cobalt mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Cell size of 10 km x 10 km. CBA scoring by sum of frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Equal intervals classification. Data sources are:
- the FRAME project database on deposits of energy critical elements;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008); lithologies of Tertiary and Quaternary ages have been excluded.

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Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Figure 10 - CBA prospectivity map for cobalt mineralization in Europe.

3.4 Natural graphite

3.4.1 Main mineral provinces for natural graphite in Europe

Even if graphite is a quite common mineral in meta-sedimentary rocks in Europe, it is rare to find enrichments that are economicaly interesting. Presently mining is taking place in only three European countries: Austria, Norway and Ukraine.

Graphite is formed when volatiles like CO_2, CH_3 and H_2O are released from organic matter during metamorphism. Chemical reduction leads to the formation of carbon and graphite. If this is deposited syn-genetically in the rock, the result is flake graphite deposit. If, however, the carbonaceous material is deposited epigenetically in veins the results is vein type graphite deposits (*Buseck and Beyssac, 2014*). The industry classifies graphite deposits into three types: flake, vein or amorphous graphite. The latter is usually not amorphous, strictly speaking, but micro crystalline, with grain size of graphite crystals less than 1 micrometer (*Beyssac and Rumble, 2014*).

In FRAME deliverable D3.3, *Sadeghi et al. (2020)* identified 30 provinces for natural graphite (Figure 11). A large number of the occurrences have unclassified genetic type due to the low number of studies available. Roughly, main areas with graphite mineralization are:

a. The Fenneoscandian shield area, of Norway, Sweden and Finland
b. The Ukrainian shield
c. Central Austria and Bavaria
d. The Iberian peninsula of Spain and Portugal

The graphite occurrences of the Fennoscandian shield are all of Proterozoic age and occur in high metamorphic grade metasedimentary rocks. Norway, Sweden and Finland have more than 50 occurrences registered in each country. The most famous or largest deposits in each country is the Skaland graphite deposits on the Senja Islands in Norway, the Nunasvarra deposit of northern Sweden and the Pipumäki occurrence of Central Finland.

The graphite occurrences of Ukraine are all located on the Ukrainien shield, which comprises archean to proterozoic rocks of metasedimentary gneisses, amphibolites and various mafic to acidic igneous rocks. The most important graphite occurrence in Ukraine is the Zavalyevskiy deposit, which is also currently the only one in production.

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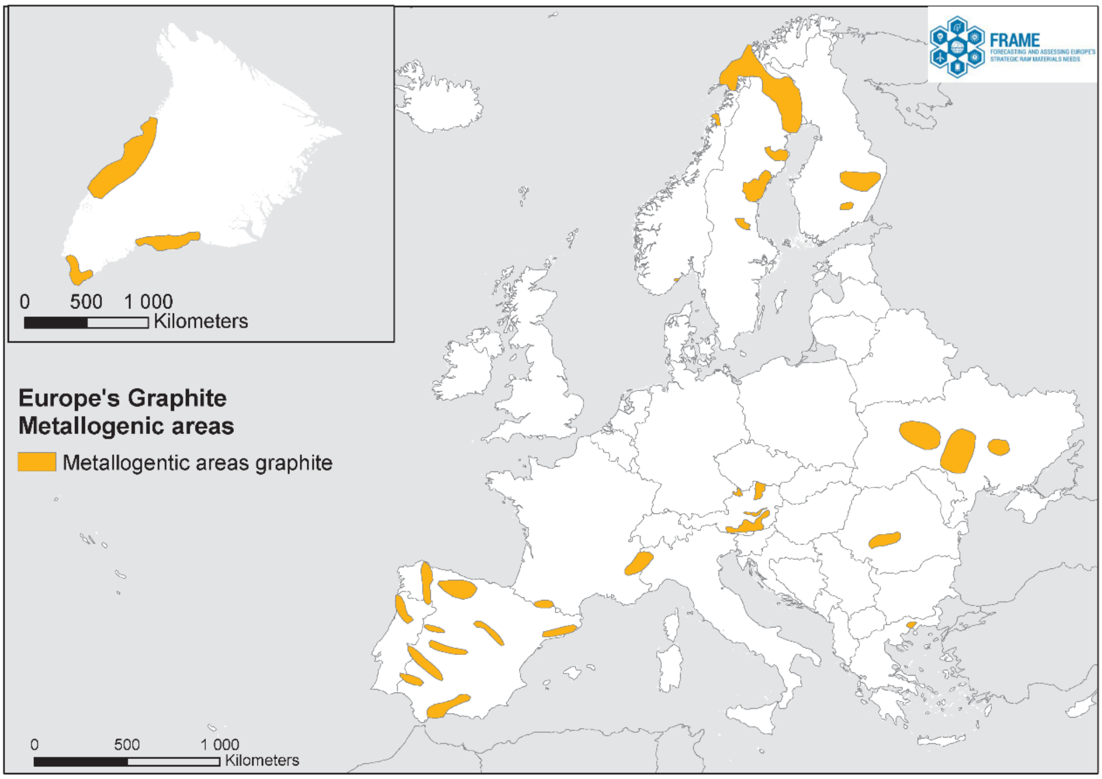


Figure 11 - Main metallogenic provinces for natural graphite in Europe and their genetic types (Sadeghi et al., 2020).

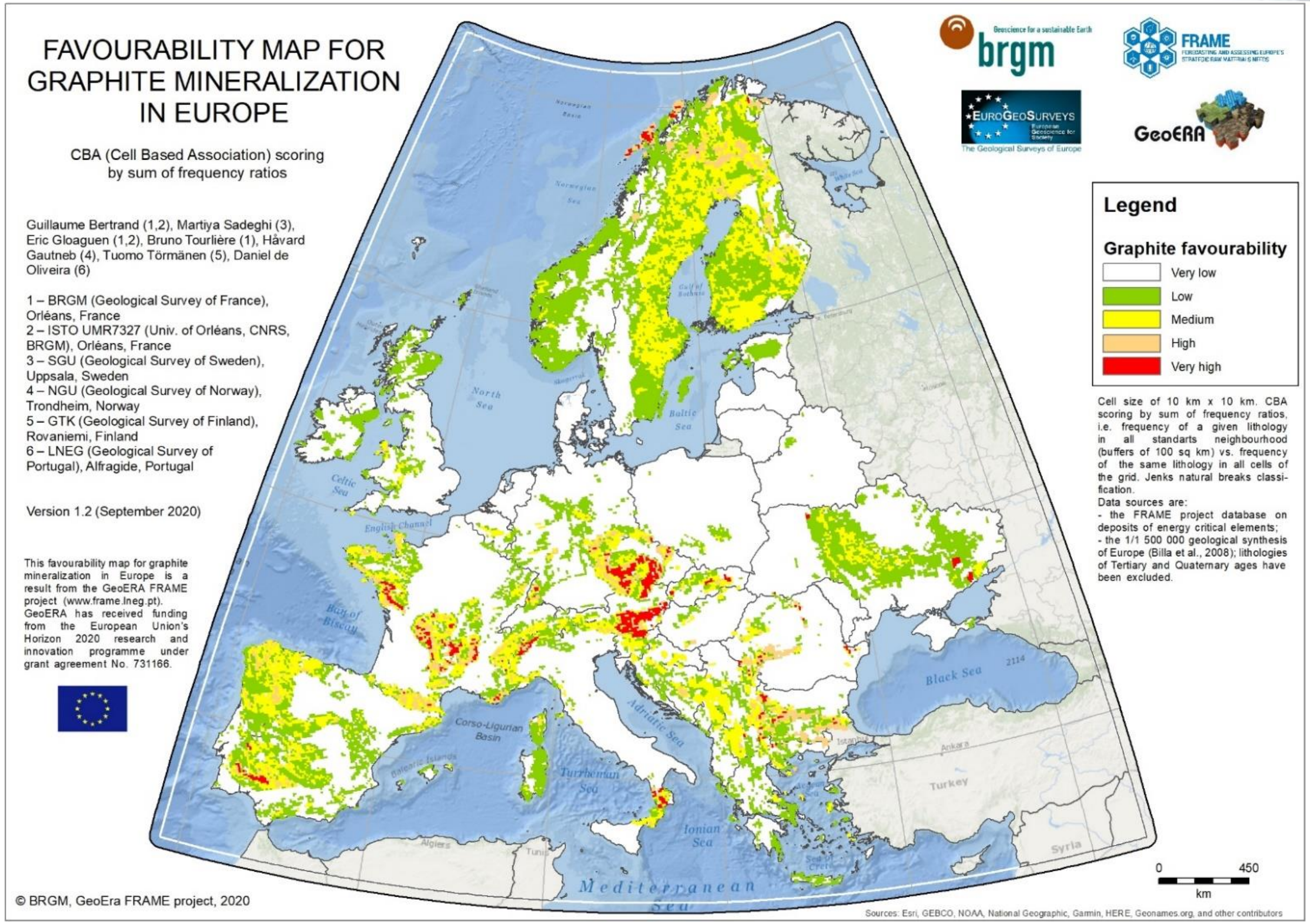
In Spain there are scattered occurrences all over the Iberian Peninsula, but few of them have been described in publications. In the Aracena mountains, in southern Spain, graphite occurrences are described from the Neoproterozoic rocks containing meta sedimentary gneisses, amphibolites and granulites.

In Austria there are 4 provinces with graphite occurrences: the Dosendorf and Moldanubikum (Bavarikum) provinces, the Veitsch nappe (Kaisersberg) and the Drau-Mur (Sothern Styria area) area.

3.4.2 CBA prospectivity map for natural graphite

First of all, one should keep in mind that the CBA map for graphite (Figure 12) does not differenciate between flake, vein and amorphous graphite. All types were included and the resulting favourability does not favour any type over the others, although metallogenic contexts could to a certain degree. Still, the CBA map shows very high favorability in areas where numerous or important graphite deposits are known. That is the case for instance in the Lofoten Islands in Norway and in Austria, which is expected owing to the many graphite occurrences known there.

In addition, the map shows high favorability in areas where no or few graphite occurrences are known. That is for instance the Evora and Extremadura Provinces in Portugal and Spain, the southern Armorican massif and western central massif in France, the Schwartzwald massif in southwestern Germany, the Czech Republic and Central Slovakia, the southwestern part of Romania, the western and southern part of Bulgaria and north Macedonia. Again, these areas should be carefully studied to confirm their favourability and assess more precisely their potential.



FAVOURABILITY MAP FOR GRAPHITE MINERALIZATION IN EUROPE

CBA (Cell Based Association) scoring by sum of frequency ratios

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Version 1.2 (September 2020)

This favourability map for graphite mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Legend

Graphite favourability

- ⬜ Very low
- 🟩 Low
- 🟨 Medium
- 🟧 High
- 🟥 Very high

Cell size of 10 km x 10 km. CBA scoring by sum of frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification.
Data sources are:
- the FRAME project database on deposits of energy critical elements;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008); lithologies of Tertiary and Quaternary ages have been excluded.

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Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Figure 12 - CBA prospectivity map for natural graphite mineralization in Europe.

3.5 Phosphates

3.5.1 Main mineral provinces for phosphates in Europe

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. The main mineral provinces for phosphate minerals in Europe presented below (Figure 13) were described in the FRAME project deliverable D3.3 by *Sadeghi et al. (2020)*.

Carbonatite

In Finland, the Devonian Sokli carbonatite complex hosts a large apatite deposit. The highest modal values of apatite are observed in phoscorite (up to 50%) (*O'Brien and Hyvönen, 2015*). The Siilinjarvi phosphate deposit is associated with a carbonatitic complex dated at ~2610 Ma (GTK unpublished report in *O'Brien et al., 2015*). In Norway, the Neoproterozoic Fen carbonatite complex is known for its Nb and REY mineralization, though it also hosts apatite-rich facies. The Seiland Igneous Province in Norway comprises Neoproterozoic to Cambrian alkaline complexes, among which the Lillebukt Complex that presents an interest for its phosphate content (*Ihlen et al., 2014*). In Sweden, the Neoproterozoic Alnö carbonatite contains ~2 Mt at a grade varying from 2 to 6% P2O5. 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 Misværdal Complex (Norway) is a Silurian alkaline complex comprizing mostly pyroxenites that are the main carriers of apatite. The Loch Borralan and Loch Loyal Silurian intrusions (Scotland, UK) host apatite-rich facies that present a potential for phosphate (*Notholt and Highley, 1981; Walters et al., 2013*). Other alkaline complexes containing apatite at a near-economic grade are found in Italy (*Stoppa et al., 2016*).

Kimberlite and lamproite

The most known lamproite in Europe is present in Spain, at Jumilla. There, Miocene jumillites host an apatite mineralization (*Venturelli et al., 1991*).

Mafic to ultramafic intrusion

In Norway, the Neoproterozoic Rogaland Anorthosite Province constitutes one of the most promising targets regarding phosphate exploitation. The Paleoproterozoic Lofoten-Vesteralen Mangerite Complex (LVMC, Norway) constitutes another interesting area regarding its potential for P (*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*).

Iron oxide apatite (IOA)

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 (ii) the Bergslagen district, with the Grängesberg mine. In Norway, the Nissedal area is known for occurrences of magnetite–hematite-apatite deposits.

Metasomatic replacement/ hydrothermal veins

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*). This was one of the most important phosphate sources in Europe from the 1850s to the Second World War (*Vindel et al., 2014*). In the Bamble-Lillesand Block (Norway), the paragneiss at Rossavika hosts pseudo-carbonatitic lenses and veins enriched in apatite. In Sweden, the REE-P mineralization occurring at Olserum, Djupedal and Bersummen present veins and vein zones hosted in metasedimentary rocks.

Sedimentary phosphorites

Three main episodes of phosphogenesis are known during the Lower Paleozoic, the Upper Cretaceous, and the Tertiary that led to the formation of sedimentary phosphorite deposits of major importance. Lower Paleozoic phosphorite constitute most of the sedimentary phosphorite in Europe, testifying for the presence of a phosphogenic

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province within the Avalon and the Baltic Platforms. Such deposits are commonly associated with glauconitic sediments or black shales (*Notholt and Brasier, 1986*).

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. These deposits reveal a significant phosphogenic episode that occurred during Cretaceous time on the NE margins of the Anglo-Paris Basin (*Jarvis, 1992*) and result in the formation of numerous phosphorite occurrences/deposits.

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), in Sicily and in Germany.

Beside the deposits formed during these three main phosphogenic episodes, it is worth mentioning a few others economically interesting mineralizations. Among these are the Proterozoic Lampinsaari deposit (Finland), Devono-Carboniferous phosphorites potentially interesting in Ireland, France, Spain, UK, Romania and Germany (*Notholt et al., 1979, 1989*).

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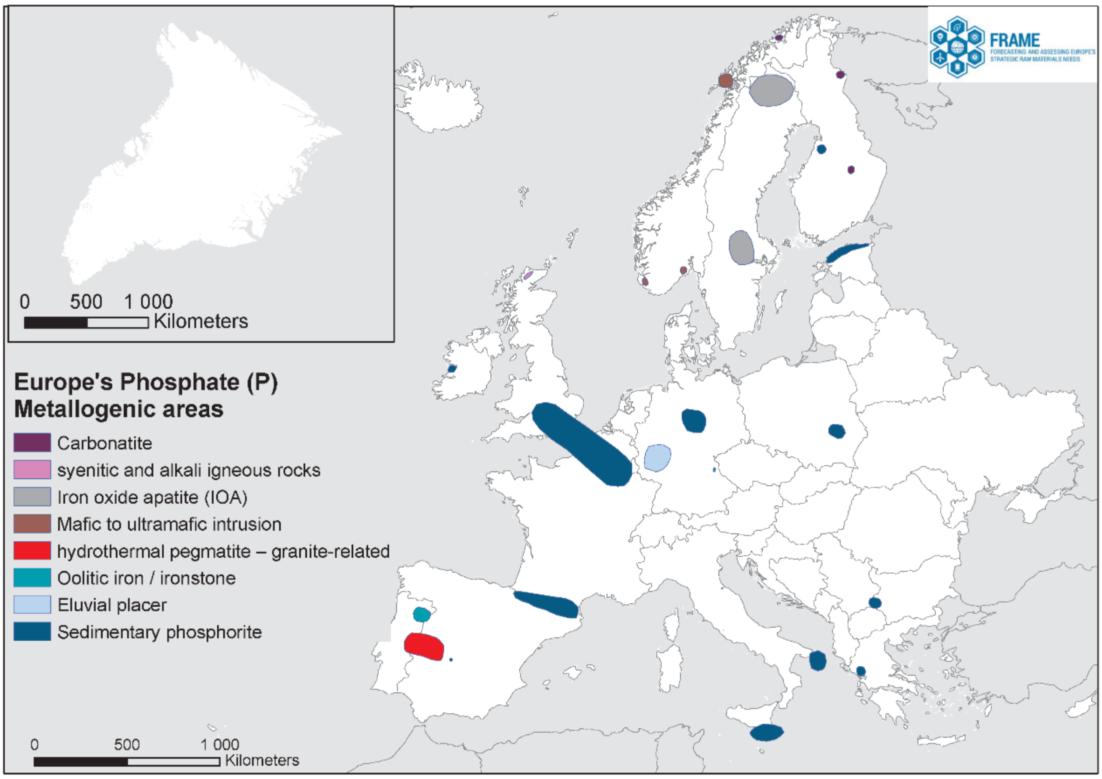
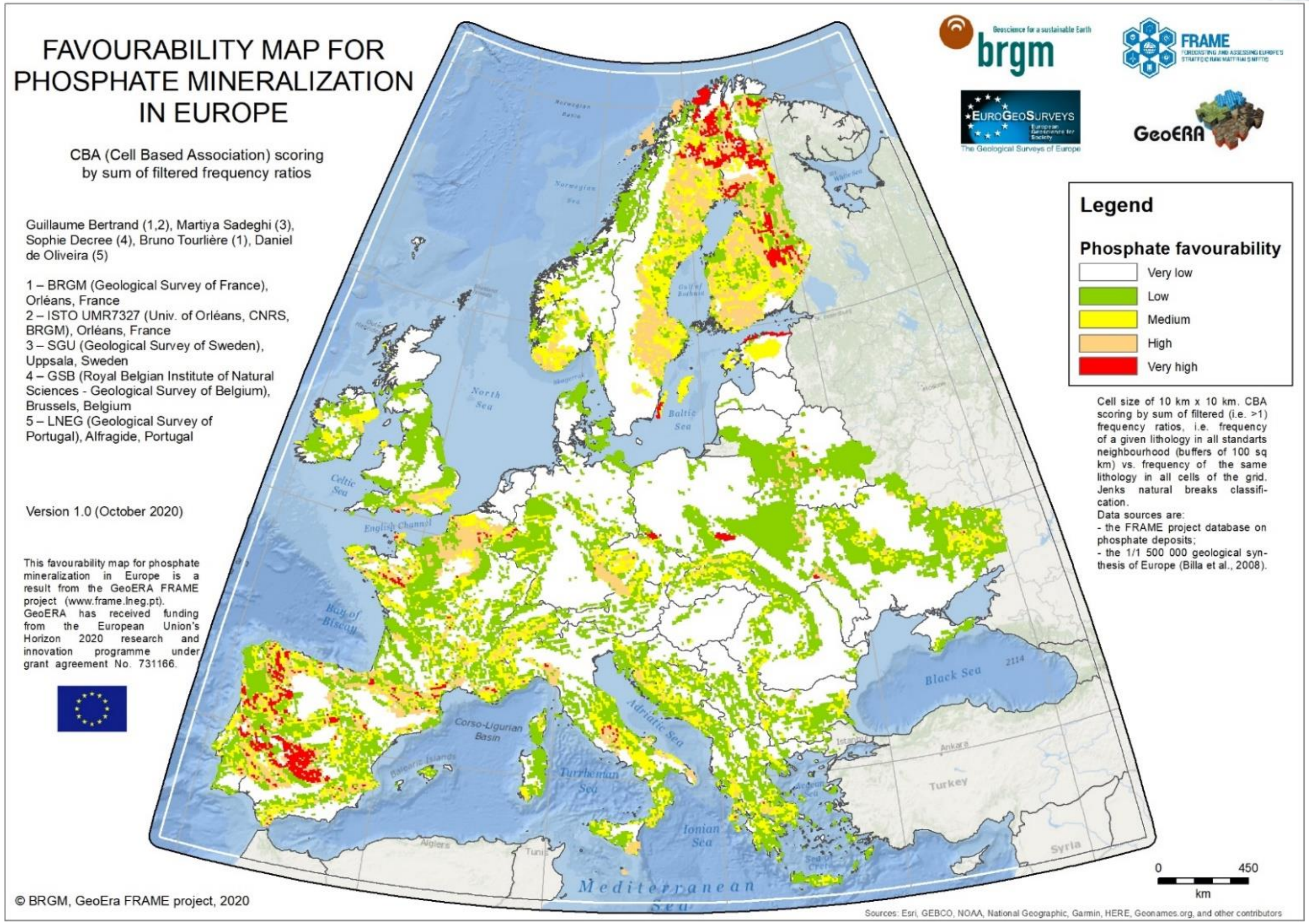


Figure 13 - Main metallogenic provinces for phosphate in Europe and their genetic types (Sadeghi et al., 2020).

3.5.2 CBA prospectivity map for phosphates

Most of the European phosphate metallogenic areas identified in Figure nnn can be found in the CBA prospectivity map (Figure 14) with high to very high favourability scores. That is for instance the case for the sedimentary phosphorite areas in the London and northern Paris basins, northern Estonian coastal area, southern Apulia and Sicily in Italy, and central Greece, or the iron oxide apatite areas in northern and central Sweden. High favourability in these regions however span much larger areas than the phosphate metallogenic areas identified by *Sadeghi et al. (2020)*. That of course could partly be an effect of the symbology and classification of scores in the CBA prospectivity map, but it could also indicates a potential more distributed than the sole metallogenic areas.

In addition, tha CBA prospectivity map highlights new prospective areas that were not identified in the main metallogenic areas. These are for instance, Galicia and northern Andalucia in Spain, Britany in France, central Apennines and Liguria in Italy, along the German-Czech Republic-Poland borders, in eastern Ukraine and along a north-south axis stretching irregularly from the Moldavia-Ukraine border northward to eastern Ukraine and Bielorussia. As for the other prospectivity maps, these areas highlighted with favourable scores need to be studied in more details to confirm their favourable potential.



FAVOURABILITY MAP FOR
PHOSPHATE MINERALIZATION
IN EUROPE

CBA (Cell Based Association) scoring
by sum of filtered frequency ratios

Guillaume Bertrand (1,2), Martiya Sadeghi (3), Sophie Decree (4), Bruno Tourlière (1), Daniel de Oliveira (5)

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2 – ISTO UMR7327 (Univ. of Orléans, CNRS, BRGM), Orléans, France
3 – SGU (Geological Survey of Sweden), Uppsala, Sweden
4 – GSB (Royal Belgian Institute of Natural Sciences - Geological Survey of Belgium), Brussels, Belgium
5 – LNEG (Geological Survey of Portugal), Alfragide, Portugal

Version 1.0 (October 2020)

This favourability map for phosphate mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Legend

Phosphate favourability
- ⬜ Very low
- 🟩 Low
- 🟨 Medium
- 🟧 High
- 🟥 Very high

Cell size of 10 km x 10 km. CBA scoring by sum of filtered (i.e. >1) frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification.
Data sources are:
- the FRAME project database on phosphate deposits;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008).

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Figure 14 - CBA prospectivity map for phosphate mineralization in Europe.

3.6 Niobium and tantalum

3.6.1 Main mineral provinces for niobium and tantalum in Europe

European Nb-Ta occurrences, and specifically those enriched in tantalum, are mainly associated with evolved granites and granitic pegmatites, and to a lesser degree, with hydrothermal systems related to granitic intrusions. Granitic pegmatites of the rare element type carrying variable proportions of niobium and in particular, tantalum, as well as similarly mineralized granites are known from the Palaeoproterozoic bedrock of the Fennoscandian Shield and several younger granites and granitic pegmatite suites in Europe (e.g. the Variscan belt of the Iberian Peninsula, the Massif Central of France and the Bohemian massif). Specifically, peraluminous granites together with granitic pegmatites of the more fractionated LCT-family (enriched in lithium, cesium and tantalum) are of primary relevance in these areas.

Niobium is also hosted by (mainly) pyrochlore-group minerals in carbonatitic as well as syenitic rocks, which have a more restricted distribution, and are typically concentrated in smaller, localized intrusions or massifs. As in the case with REE-mineralization hosted by such rocks, the most important European deposits are characteristically associated with alkaline–peralkaline, mostly plutonic rocks and carbonatites that have formed in intracontinental rift-settings during extensional episodes (e.g. *Goodenough et al. 2016, and references therein*).

Secondary deposits (placers) also occur, but they have a significantly more restricted distribution than the primary deposit types. The main mineral provinces for tantalum and niobium in Europe presented in Figure 15 and Figure 16, respectively, were described in the FRAME project deliverable D3.3 by *Sadeghi et al. (2020)*.

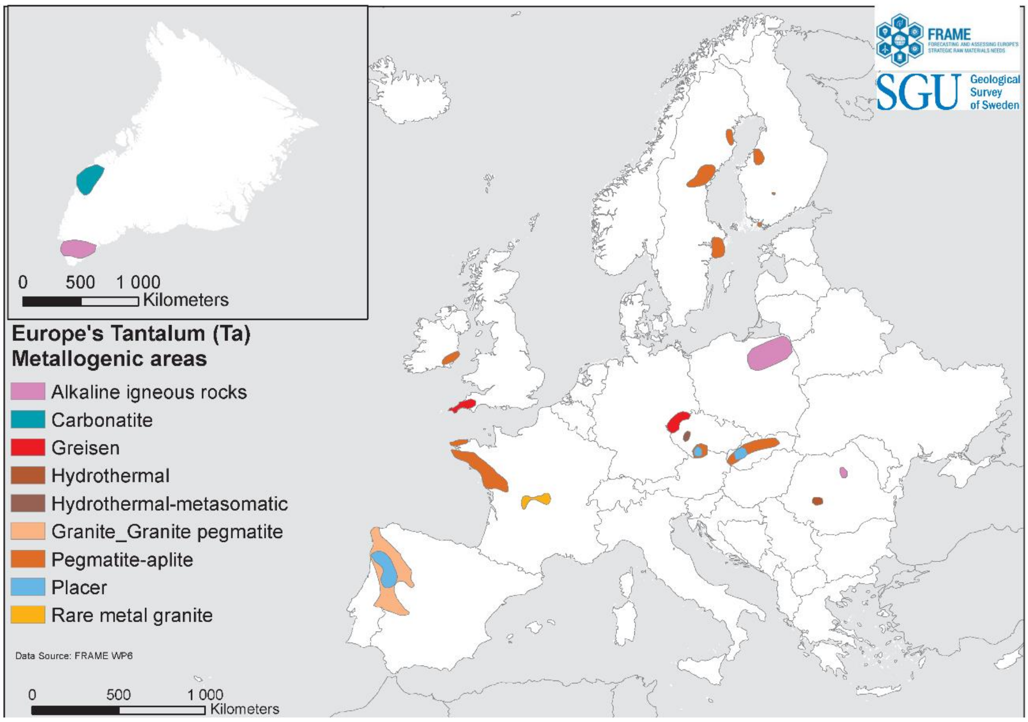

Figure 15 - Main metallogenic provinces for tantalum in Europe and their genetic types (Sadeghi et al., 2020).

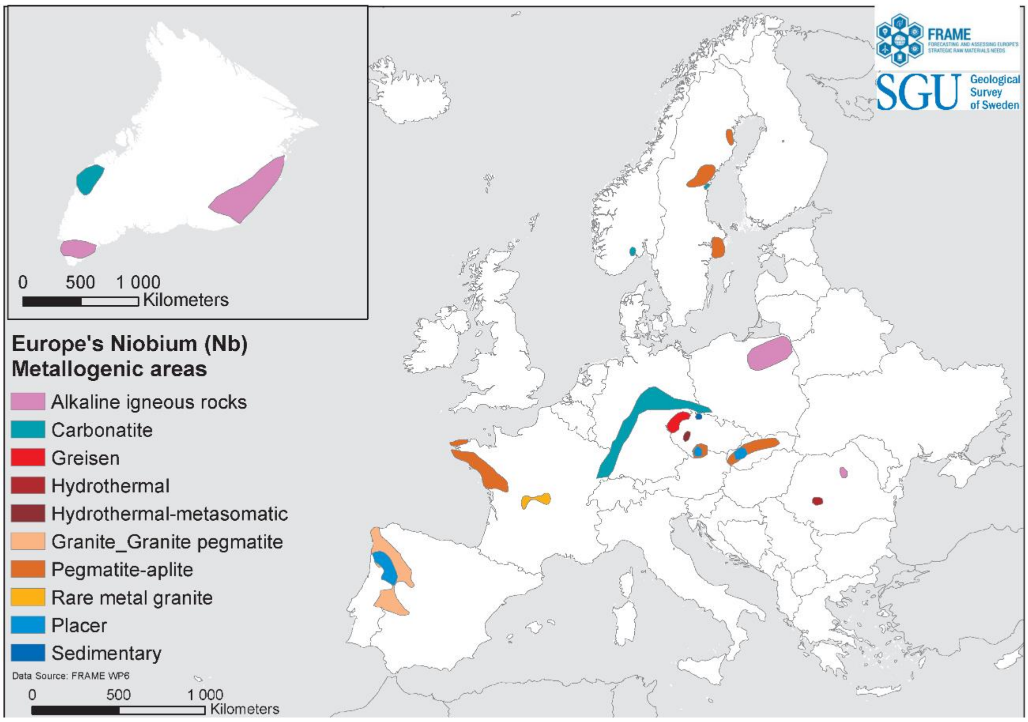

Figure 16 - Main metallogenic provinces for niobium in Europe and their genetic types (Sadeghi et al., 2020).

3.6.2 CBA prospectivity map for tantalum

The CBA favourability map for tantalum (Figure 17) shows favourable areas in French Brittany and Massif Central, in Czech Republic, Slovakia and eastern Austria, which is generally in accordance with Ta mineralisations that are known in these regions. Contrarily, several Ta deposits and occurrences are known in central Sweden and Finland where the favourability appears low to moderate.

The map also shows highly favourable areas in Iberia, where numerous Ta deposits are known. However, the favourability maps highlight areas where few or no Ta deposits.

are known, such as NE Galicia, the Principado de Asturias or Extremadura in Spain. Similarly, the Pyrenees mountains along the Spanish French border, the western Alpine arc, and Calabria in southern Italy appear highly favourable while few or no Ta deposits are reported there.

These favourable areas need to be confirmed by more focused and detailed studies, to confirm their potential. Still they already are interesting indications to guide future exploration works.

3.6.1 CBA prospectivity map for niobium

The CBA maps for niobium (Figure 18) and tantalum (Figure 17) may appear, to a certain degree, relatively similar, as the two elements co-exist in many deposits, but they are not identical. As for tantalum, the favourability for niobium is high in Iberia, with very high favourability in Norte and Centro in Portugal, and in Galicia, Principado de Asturias, southern Castilla y Leon, Extremadura and northern Andalucia in Spain. Some areas where no or few Nb deposits are reported are also highly favourable, such as the western Alpine arc, Calabria in southern Italy, Macedonia in northern Greece, southern Bulgaria and, to a lesser degree, Corsica.

Several areas with known Nb deposits also appear favourable, such as the Vestfold and neighbouring regions in Norway, the Czech Republic-Slovakia area, and the French Brittany and Central Massif. As for tantalum, central Sweden and Finland surprisingly display a low to medium favourability despite numerous Nb deposits reported there.

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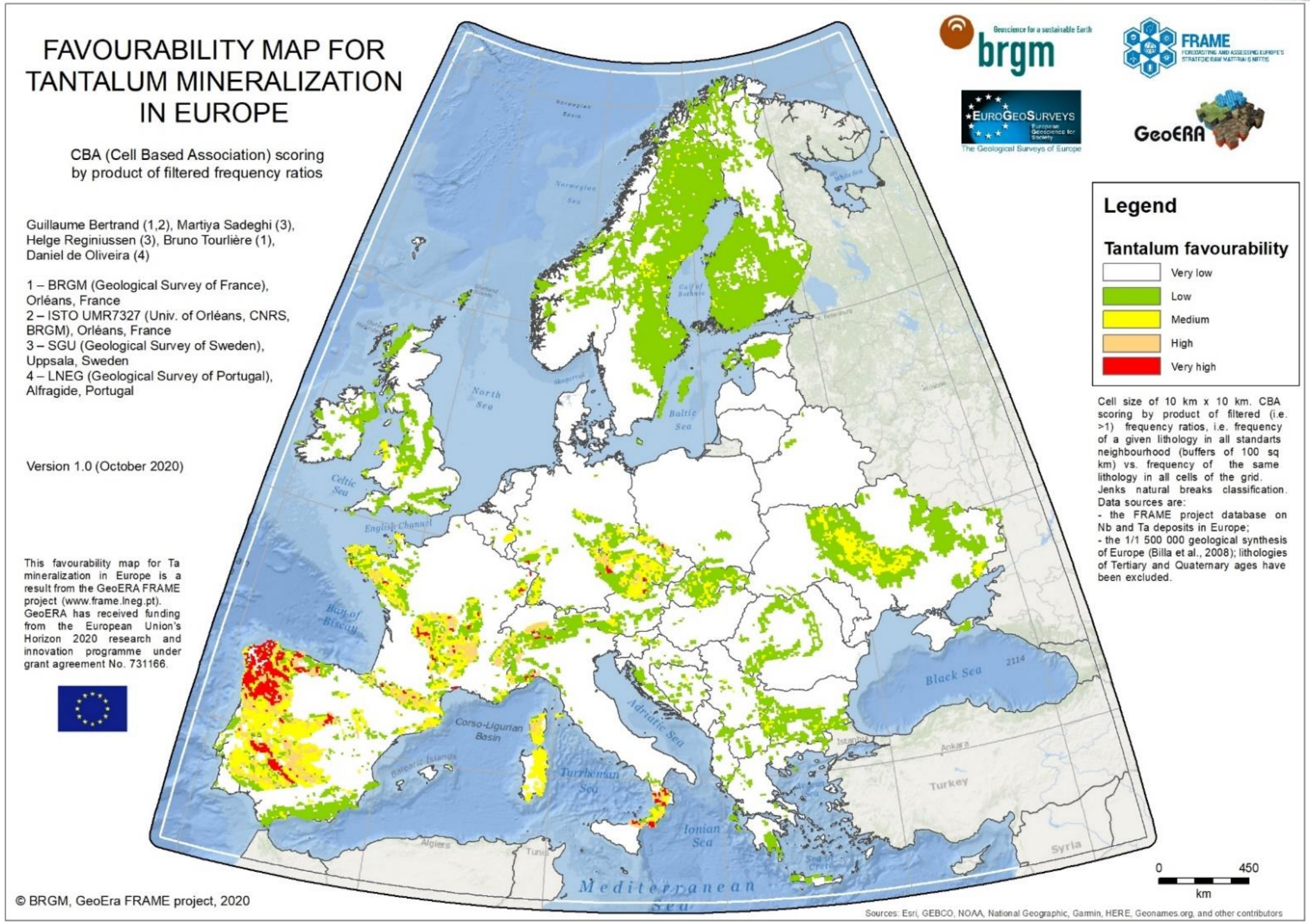

FAVOURABILITY MAP FOR TANTALUM MINERALIZATION IN EUROPE

CBA (Cell Based Association) scoring by product of filtered frequency ratios

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Version 1.0 (October 2020)

This favourability map for Ta mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Cell size of 10 km x 10 km. CBA scoring by product of filtered (i.e. >1) frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification. Data sources are:
- the FRAME project database on Nb and Ta deposits in Europe;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008); lithologies of Tertiary and Quaternary ages have been excluded.

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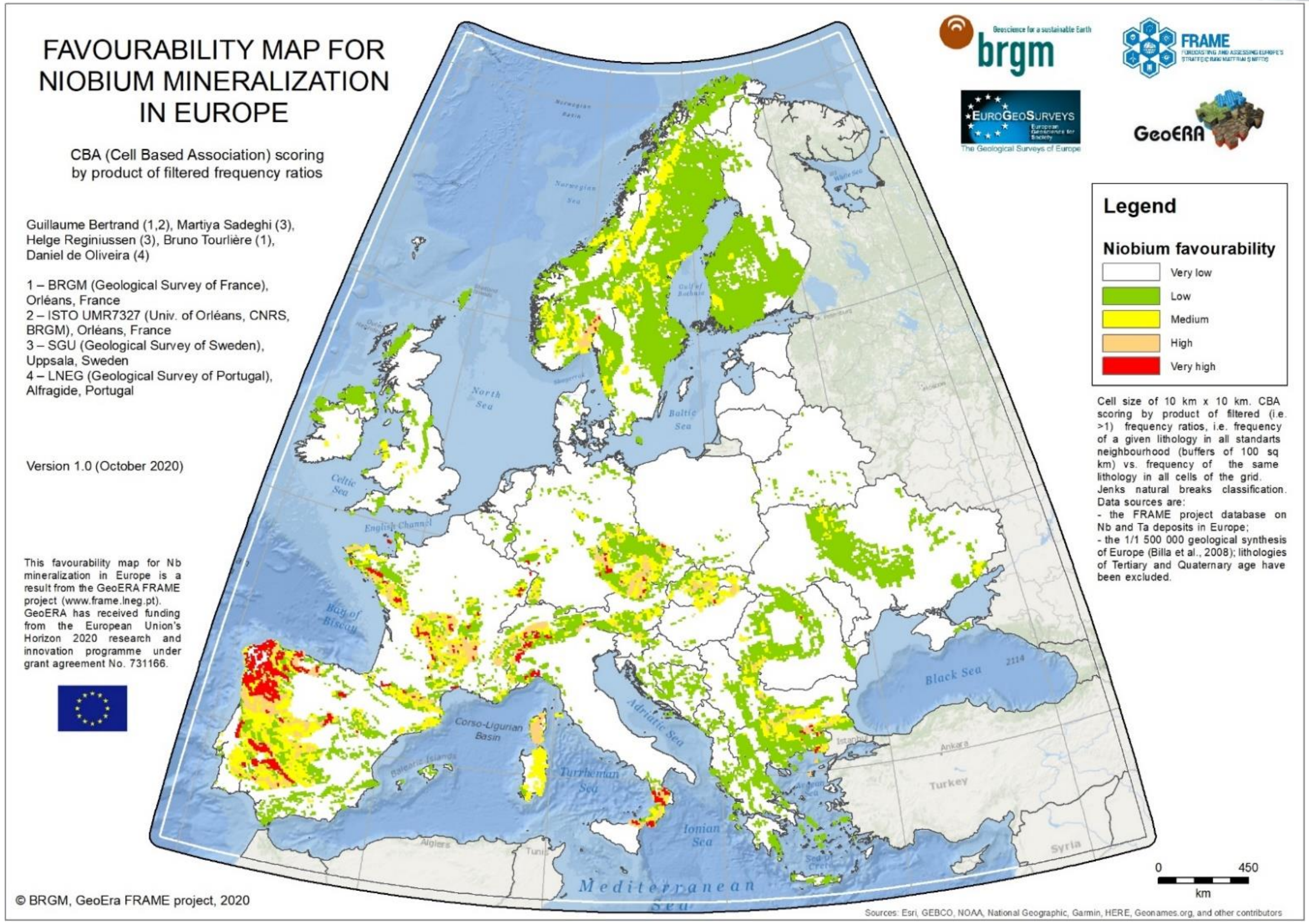
Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Figure 17 - CBA prospectivity map for tantalum mineralization in Europe.



FAVOURABILITY MAP FOR NIOBIUM MINERALIZATION IN EUROPE

CBA (Cell Based Association) scoring by product of filtered frequency ratios

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Version 1.0 (October 2020)

This favourability map for Nb mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Legend

Niobium favourability
- ☐ Very low
- 🟩 Low
- 🟨 Medium
- 🟧 High
- 🟥 Very high

Cell size of 10 km x 10 km. CBA scoring by product of filtered (i.e. >1) frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification. Data sources are:
- the FRAME project database on Nb and Ta deposits in Europe;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008); lithologies of Tertiary and Quaternary age have been excluded.

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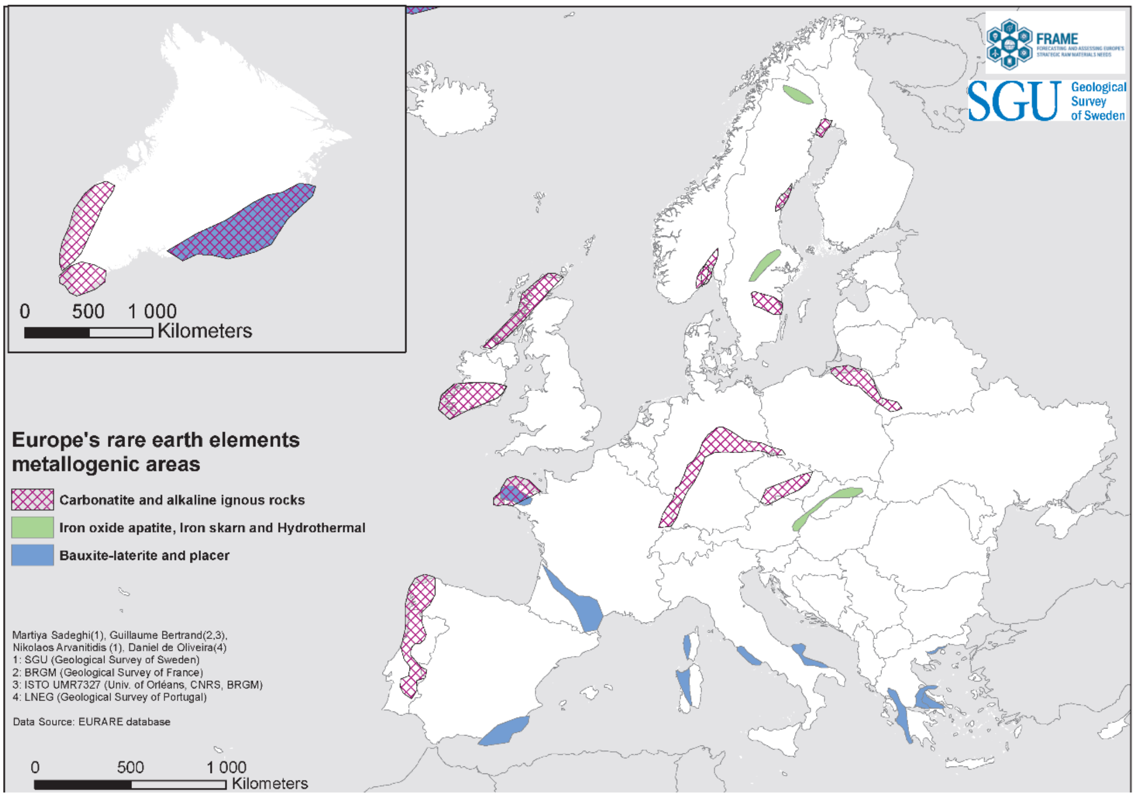
Figure 18 - CBA prospectivity map for niobium mineralization in Europe.

3.7 Rare earth elements

3.7.1 Main mineral provinces for rare earth elements in Europe

A simplified metallogenetic map of REE (Figure 19) has been presented in FRAME deliverable D3.3 by *Sadeghi et al. (2020)*. This map shows overall distribution and potential of REE mineral exploration targets based on the different genetic types' classification. The carbonatite and alkaline igneous rocks are presented separately, because of the significant potential of tonnage and grade they commonly host. The secondary REE mineral resources are presented as a separate target area related to bauxite, laterite and placer deposits.



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Data Source: EURARE database

Figure 19 - Main metallogenic provinces for rare earth elements in Europe and their genetic types (Sadeghi et al., 2020).

Alkaline contexts

The most important primary deposits with high grade and tonnage are typically associated with alkaline-peralkaline igneous rocks and carbonatites formed in extensional

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intracontinental rifts (*Chakhmouradian and Zaitsev, 2012; Goodeough et al., 2016*). Europe is characterized by numerous deep, intracontinental extensional zones and rifts which contain alkaline igneous rocks. These vary in age from the Paleo- and Mesoproterozoic of the Fennoscandian shield, via the Mesoproterozoic Gardar Province in SW Greenland to the Cenozoic rifts around the Mediterranean. REE occurrences of potential economic interest are commonly associated with peralkaline syenitic intrusions in these igneous provinces. The Norra Kärr deposit consists of a c. 1.5 Ga old, small, complex intrusion of agpaitic rocks located east of lake Vättern in southern Sweden (cf. *Jonsson 2013 and references therein*). Other examples of syenitic intrusions in Sweden with possible potential for REE include the Permian Särna nepheline syenite intrusives in western central Sweden.

Relatively few alkaline igneous intrusions outside the Nordic countries have known potential REE resources. One such example is the Cnoc nan Cuilean intrusion of the Loch Loyal Syenite Complex in north-west Scotland. This Silurian-age syenitic intrusion contains mafic syenites and syenodiorites that are rich in the LREE-bearing mineral allanite.

Carbonatites

Carbonatites are igneous carbonate rocks in which the modal percentage of carbonate exceeds 50% (*IUGS, Le Maitre, 2002*). Carbonatites often occur in continental extensional or rift settings, in several cases in association with alkaline to peralkaline syenitic rocks. The origin of carbonatite magmas, whether they formed from liquid immiscibility with silicate melts, or as directly mantle-derived small-degree partial melts, continues to be debated. Important ore minerals for REE in carbonatites is typically carbonates/fluorocarbonates (e.g. ancylite, bastnäsite, parasite, synchysite) and phosphates (e.g. apatite, florencite, monazite), although significant concentrations may also be found in oxides and silicates.

High concentrations of REEs value in whole rock, and some enrichments of LREE, have been identified in sövite (calcite carbonatite) from the Alnö alkaline complex in Sweden, which includes both silicic (syenitic) and carbonatitic rocks. North of Alnö proper, several intrusions have been identified by the geological survey of Sweden north of the village Söråker, and some of them show elevated REE concentrations in carbonatite. Similar, but

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smaller dykes occur in the Kalix area, close to the Finnish border in northeasternmost Sweden.

The Sokli intrusion in Finland consists of a carbonatite core surrounded by carbonatite and a wide fenite aureole. It is part of the Kola alkaline province, which consists of nearly thirty Devonian, ca. 360-380 Ma alkaline intrusions of various sizes. The main REE-rich carbonate minerals recognised in the Jammi carbonatite veins at Sokli are ancylite and bastnäsite. They are strongly enriched in LREE, P, F, Sr and Ba. Apatite occurs as large and elongated grains closely associated with monazite.

The Fen Complex, an early Cambrian intrusive complex of alkaline rocks and carbonatites, is situated in Nome municipality, Telemark County, Norway. There are several different igneous rocks within the complex, including basic, lamphrophyric and carbonatitic rocks. Of these, the carbonatitic rocks are specifically interesting for REEs. The REE mineralization mainly consists of monazite, bastnäsite, synchysite and parisite (*Andersen, 1986; Lie & Østergaard 2011a*).

Carbonatites occur in many of the younger extensional zones and intra-continental rift systems in Southern Europe, but few are exposed. One carbonatite that has been assessed for its REE potential is the buried Delitzsch carbonatite complex, containing the Storkwitz deposit, which lies within a Cretaceous rift zone in Germany. It is presently under exploration by Seltenerden Storkwitz AG.

Iron oxide-apatite and Iron skarn mineralization

Magnetite-(hematite)-apatite ores of the Kiruna type comprise the biggest iron mines in Europe today. Typically, these genetically debated deposits (cf. *Parak, 1975, Hitzman et al. 1992*) are hosted by felsic to intermediate metavolcanic rocks of ages between c. 1.90-1.87 Ga. Important examples of such deposit type include Kiirunavaara and Malmberget (*Bergman et al., 2001*) in northernmost Sweden, and Grängesberg-Blötberget-Idkerberget in Bergslagen, south central Sweden (*Sadeghi, 2019; Jonsson et al., 2019 and references therein*). In the Olserum area, in the Västervik region, are vein or schlieren-hosted REE-rich mineralizations associated with iron oxides (*Gustafsson, 1992*). Another example is the Kodal deposit located in the Paleozoic alkaline province of the Oslo rift in southern Norway, which forms a Fe-Ti-oxide-rich pyroxenite dyke (e.g. *Ihlen et al., 2014*).

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The Bastnäs-type deposits (*Geijer, 1961*) are located in the Palaeoproterozoic Bergslagen ore province of south-central Sweden, where they form a discontinuous, narrow belt of approximately 100 km length. LREE-enriched deposits are located mainly in the Riddarhyttan-Bastnäs area, and deposits showing enrichment in LREE and Y+HREE are mainly located in the Norberg district (*Holtstam & Andersson, 2007*). Typical host minerals comprise cerite, törnebohmite and allanites (sensu lato), as well as REE-fluorocarbonates such as bastnäsite (cf. *Jonsson et aL, 2014; Holtstam & Andersson, 2007; Andersson, 2004*). A large number of these minerals have their type localities among the Bastnäs-type deposits.

Metallogenic area for REE asscoaited with granite and granitic pegmatite

This type of mineralization occurs in several granite intrusions and numerous granitic pegmatite fields in the crystalline bedrock of the Fennoscandian shield. These intrusive rocks range in age from around 1.82 to c. 1.0 Ga, during the successive growth of the Fennoscandian crust (*Romer & Smeds, 1994, 1997*). Additionally, the potential for new discoveries is reasonably high. The highest contents of REE are found in some pegmatite-hosted oxides, phosphates and silicates (e.g. samarskite and euxenite-type minerals, monazite and xenotime, yttrialite-fluorthalenite, fergusonite, gadolinite, yttrotantalite. The most important granitic pegmatites and granitoids with potential for REE mineralization are, Tåresåive in northern Sweden (Norrbotten lithotectonic unit), Näverån in Central Sweden (close to the Caledonides), granitoids in Bergslagen (e.g., Ytterby), and granite in the southwestern part of Sweden, (e.g., Balltorp), more details can be found in *Sadeghi, 2019 and Sadeghi et al., 2020c*)

Allanite-bearing pegmatites are common and have variable LREE/HREE ratios. One example of this type of deposit is the granitic REE-rich pegmatite at Gloserhei in the Froland community in southern Norway, which is famous for its large allanite crystals, weighing up to 5 tons. This pegmatite is part of the Sveconorwegian South Norwegian Pegmatite Belt which extends from Kragerø in the NE to Kristiansand in the SW. The Høgtuva Be-REE-U-Sn-mineralization and Tysfjord granite in central Norway are two examples of potential granite-hosted deposits. Both mineralizations are related to Proterozoic metamorphized granites of the Trans-Scandinavian Igneous Belt (TIB). Several hydrothermal deposits in granite breccias or felsic gneiss occur in Greece and

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contain anomalous values of REEs. Examples of these occurrences are, Samothrace Island and Esochi – N. in Greece.

Metallogenic area for REE associated with laterite/Bauxite

Bauxite deposits occur along the northern shore of the Mediterranean Sea, from Spain to Turkey, encompassing Greece, parts of southern France, Bosnia and Herzegovina, Hungary and Italy (*Bárdossy, 1982; Özlü, 1983*).Many of these bauxites, which formed by intense lateritic weathering of residual clays, are currently mined for aluminium, and the red mud waste from their processing represents a potential REE resource (*Deady et al., 2014*). Similar detrital REE minerals are also accumulated in the Hungarian bauxite deposits (*Bardossy et al., 1976*).

Greece is the only EU country with extensive but low-grade nickel laterites. The Greek laterites are unique in the world in that they are sedimentary and have originated by transport and sedimentation of laterite-derived material. Among the main factors controlling the REE content in laterites are the composition of the rock source, the duration of the lateritisation process, the size of the ore bodies, the distance of the transportation, the pH and Eh conditions (*Economou-Eliopoulos et al., 1997*).

Metallogenic area for REE asscoaited with placers

An example of a placer deposit is found in Vale de Cavalos in Portugal, where an Ordovician sedimentary succession includes quartzites that are rich in the REE-bearing minerals monazite and zircon. The Aksu Diamas region in Turkey hosts alkaline volcaniclastic rocks of Cenozoic age that locally have significant concentrations of heavy minerals hosted in placer deposits. Placers of grey monazite nodules are also found in France, mainly in Brittany (*Donnot et al., 1973*), formed from low-grade metamorphosed black shales of Dinantian or Ordovician age, or even from Upper Precambrian series (Brioverian). Similar layers of shales with monazite nodules and associated placers (but of lesser interest) are also known in the southern Massif Central, in the Ardennes and in the French Pyrennees (*Lacomme et al., 1993*). In the Västervik region in southeastern Sweden, several occurrences of U-rich, REE-bearing minerals have been identified in quartzite-dominated Palaeoproterozoic metasedimentary successions (e.g. *Gustafsson, 1992*). These are interpreted to represent paleoplacer-type.

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3.7.2 CBA prospectivity map for rare earth elements

The rare earth elements (REE) dataset that was used to build the CBA prospectivity map (Figure 20) contains deposits that are located essentially in the Fennoscandian shield and, to a lesser degree, in the Alpine domain of southeastern Europe, in Austria and in the French Britany. That partly explains why these regions appear more favourable, with high favourability scores in southern Norway, western Sweden, southern Finland, along the Alpine front and in the Balkan region, and in Britany. Few supergene deposits were available in the input dataset, and most were bauxite-laterites in Greece and placers in Britany. That also explains why these domains appear favourable while other metallogenic areas for supergene deposits in southern Europe have lower favourability scores (Andalucia in Spain, Occitane in France, Corsica, Sardinia, Lazio and Apulia in Italy).

Nevertheless, the CBA prospectivity map for REE highlights new areas with high favourability scores that might deserve further attention. These are, for instance, the Carpathian range in Romania, the Balkan countries and particularly southern Serbia, the Alpine front in northern Italy, the southern Svecofennian domain in Finland. High favourability scores in Sweden are observed beyond the boundaries of main metallogenic areas, which suggests a broader potential of these regions.

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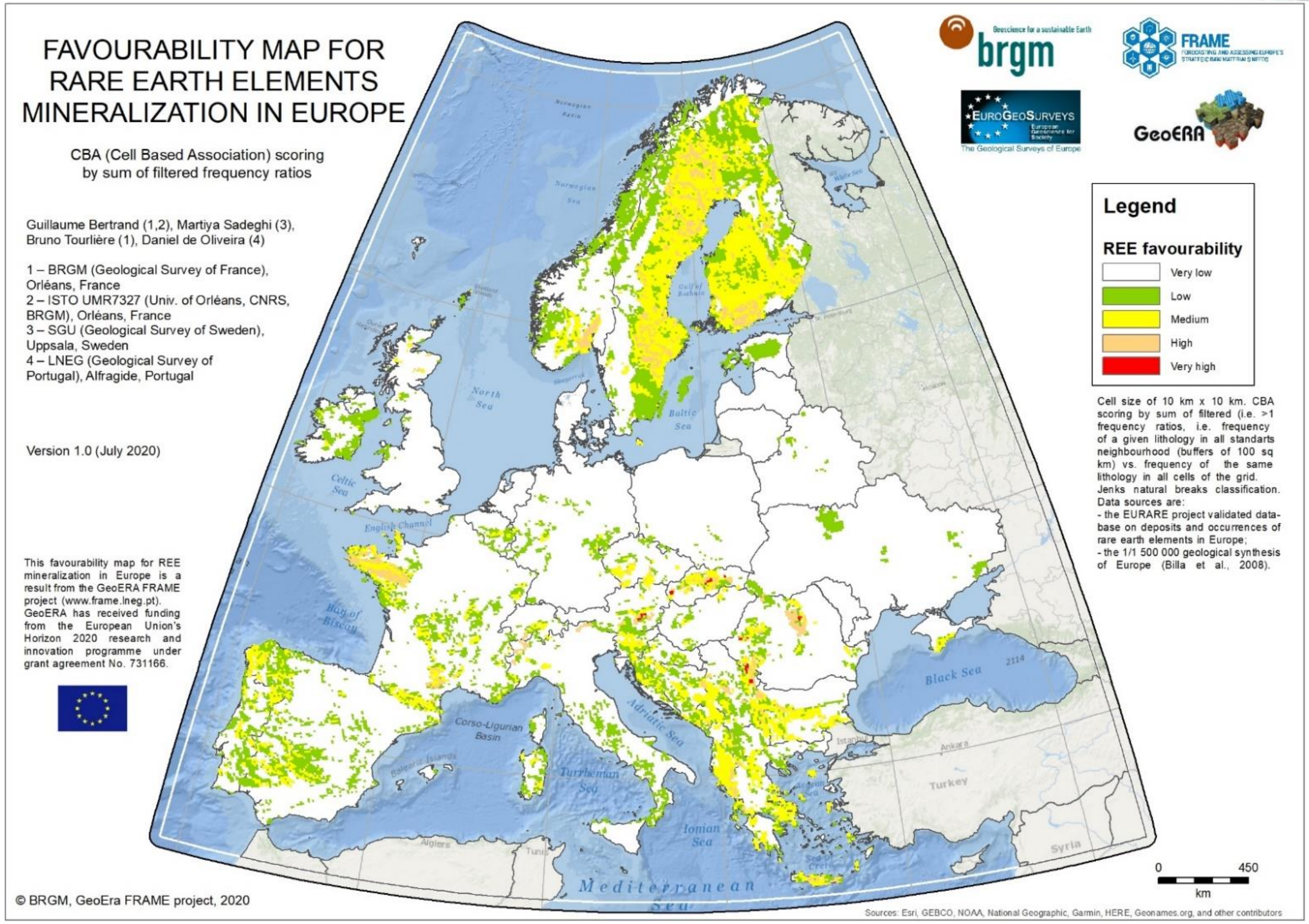

FAVOURABILITY MAP FOR
RARE EARTH ELEMENTS
MINERALIZATION IN EUROPE

CBA (Cell Based Association) scoring
by sum of filtered frequency ratios

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Version 1.0 (July 2020)

This favourability map for REE mineralization in Europe is a result from the GeoERA FRAME project (www.frame.lneg.pt). GeoERA has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 731166.

Cell size of 10 km x 10 km. CBA scoring by sum of filtered (i.e. >1 frequency ratios, i.e. frequency of a given lithology in all standarts neighbourhood (buffers of 100 sq km) vs. frequency of the same lithology in all cells of the grid. Jenks natural breaks classification. Data sources are:
- the EURARE project validated database on deposits and occurrences of rare earth elements in Europe;
- the 1/1 500 000 geological synthesis of Europe (Billa et al., 2008).

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Sources: Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, Geonames.org, and other contributors

Figure 20 - CBA prospectivity map for rare earth elements mineralization in Europe.

3.8 Diffusion of the CBA prospectivity maps

The seven CBA prospectivity maps presented above are usefull only if they can be easily identified and consulted by end users. To ensure that they are easily and freely available, they are distributed via the online EGDI (European Geological Data Infrastructure) online data platform (http://www.europe-geology.eu/).

CBA favourability maps are included as information layers in the EGDI map viewer (Figure 21), allowing to display them with any other geoscience-related data layers and to benefit from tools and utilities of the plarform. In addition, the maps are available for download in pdf formats as they are displayed in the previous sections (hypertext link “Download prospectivity map of Europe” in the left-hand side column on Figure 21). The full metadata of each map is also available by clicking on the “information” tab (little white “i” in a dark-blue circle) of the map layer in the left-hand side column. This will allow a wide and seamless access to these prospectivity maps, even after the lifetime of the FRAME project, as the EGDI platform is kept maintained independently from the project.

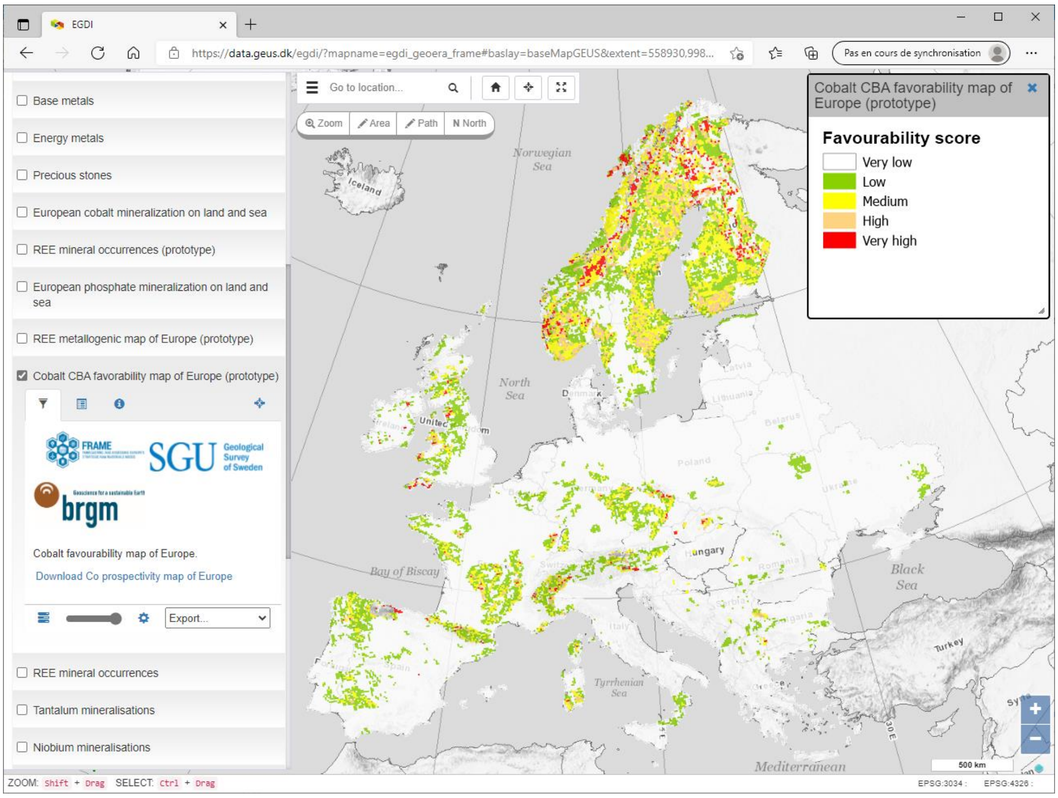

Figure 21 - View of the CBA prospectivity map for cobalt in the EGDI web portal.

4 Prospectivity mapping with the hybrid fuzzy-Weightof Evidence approach

4.1 Introduction to Fuzzy and Weight of Evidence approaches

The fuzzy logic technique is flexible and allows the decision-making process of an exploration geologist to be replicated, and therefore the technique is suitable for a greenfields exploration terrain. The fuzzy logic technique is based on fuzzy-set theory, which was first introduced by *Zadeh (1965)*.

In fuzzy-set theory the membership of a set is defined on a continuous scale from full membership to full non-membership (e.g., from prospective to non-prospective). A fuzzy set of A is a set of ordered pairs:

$$A = \{[x, \mu A(x)] | x \in X\}$$

where, X is a collection of objects and μA(x) is the membership function of x in A. This means that μA(x) defines the degree of membership of x in A. This membership function can be linear or non-linear.

The first step in prospectivity analysis is to define an exploration model that will form the basis for the selection of the evidential (supporting) datasets. The second step is the pre-processing of the selected data and classification of the derived maps into meaningful map patterns (i.e., anomaly maps or evidence maps). A set of map data is first reclassified into evidence maps, then each map "fuzzified" or rescaled from zero to one (from non-prospective to prospective for deposits concerned) based on subjective expert opinions.

The fuzzy large function is one example of functions to be used for re-scaling the data sets:

$$\mu(x) = \frac{1}{1 + \left(\frac{x}{f2}\right)^{-f1}}$$

where, **f1** = spread (range from 1 to 10) and **f2** = midpoint (range from min to max of input data). The spread parameter defines the shape of the function, and the midpoint parameter defines the fuzzy membership value of **0.5** within the input data range. By changing these parameter values, it is possible to create several input maps to be tested in the data integration process.

The rescaled evidence maps are then integrated in a simple combination using fuzzy operators (*Bonham-Carter, 1994*) to produce a single prospectivity map for the deposit type in question. This map identifies the most favourable areas for the occurrence of mineral deposits based upon the input evidence maps selected and processed by the expert. In the areas highlighted on the prospectively map, all the exploration criteria spatially coincide. Commonly used fuzzy operators include 'Fuzzy AND', which is a minimum operator (logical intersection), and 'Fuzzy OR', which is a maximum operator (logical union), 'Fuzzy SUM', which is a multiplication operator and produces a decreasive effect, 'Fuzzy PRODUCT', which is "1-minus" multiplication operator and produces an increasive effect, and the 'Fuzzy GAMMA' operator, which is combination of the SUM and PRODUCT fuzzy operators (*Bonham-Carter, 1994*).

The weights-of-evidence (WofE) method is a statistical method for quantifying spatial association between mineral deposits and geological features (*Bonham-Carter et al., 1988, 1989; Agterberg, 2011; Bonham-Carter, 1994; Carranza and Hale, 2002*). WofE is typically applied to exploration situations in which there are an adequate number of mineral deposits or occurrences already known. WofE is a discrete multivariate method that was first applied to combine spatial data and make predictive mineral potential maps (*Bonham-Carter et al., 1988*). It is easily implemented within a GIS computing environment. This method employs Bayesian conditional probability to combine predictor patterns of geological features that have a spatial association with the spatial distribution of mineral deposits.

The following formulation of the Bayesian probability model is summarized from *Bonham-Carter (1994)* and *Bonham-Carter et al. (1989)*. WofE is a data-driven method based on the Bayesian theorem and its fundamental concept of prior and posterior probabilities. The method combines statistically diverse geoscientific data that represent ore-controlling factors by weighting their deposit-indicator evidence using training sites of known mineralization to create a posterior probability map. This technique allows spatial relationships between selected predictors (evidence maps) and the location of known mineral occurrences to be statistically evaluated. The strength of the spatial association is assessed by calculating a pair of weights, W+ and W-, determined from the degree of overlap between the training sites (known deposits or occurrences) and an evidence map. Weights are relative, dimensionless values, which depend on the ratio of training sites that fall on a particular map class to the total number of sites, against, the

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ratio of the particular map class area to the total map area. A positive correlation between sites and a map class is represented by W+ > 0 and W– < 0 (there are more sites in a particular map class than would be expected due to chance); a negative correlation by W+ < 0 and W– > 0. Where no spatial association exists (i.e.—the two ratios are equal), the weights are both zero. Where data are unknown or missing (incomplete evidence map coverage), the weights are assigned the value zero (*Bonham-Carter, 1991*). The contrast value (C = W+- W-) was introduced by *Agterberg et al. (1990)*, and reflects the strength of spatial association. A C value of 0 indicates no spatial association between occurrences and evidence map, while a large C value (more than 1) indicates a strong association. *Mihalasky (2006)* divided WofE in to three main procedures: 1) measurement of spatial association between training sites and the evidence maps, 2) optimization of the evidence maps for prediction, and 3) combination of the predictor maps to create favourability maps.

4.2 Hybrid Fuzzy-Weight of Evidence (Fuzzy-Wofe) method

The Fuzzy Wofe approach (*Cheng and Agteberg, 1999*) can be either (a) purely datadriven, if a data-based function is used for the calculating fuzzy membership values or (b) hybrid knowledge-data driven, if a knowledge-based function is used for calculating fuzzy membership values. In the FRAME project we demonstrate a hybrid Wofe approach to pan European selected critical raw materials (e.g., Nb, Ta, Graphite, P, Li, and Co).

Fuzzy weight of evidence (Fuzzy-WofE) is the fuzzy analog of the ordinary WofE method (more details on methodology can be read from *Porwal et al., 2003* and *Porwal et al., 2006 and references therein*). This method provides a better theoretical framework for handling the complexity of modeling multi-class data in a flexible and consistent way.

In brief, the followed method estimates the fuzzy favorability membership value for each of the jth class in the ith lithology related variable, using the knowledge-based logistic membership function (*Porwal et al., 2003*):

$$\mathrm{\mu A{\sim}xij} = \frac{1}{1 + \mathrm{e}^{-\mathrm{a(xij-b)}}}$$

where **b** is the inflexion point (values between 0 and 100), **a** is the slope of the function and **xij** the overall class score of the ***j***th class in the ***i***th lithology related variable.

The overall class score is calculated by the following equation:

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$$Xij = Wj * Wi$$

where w_j is the class weight of the j^{th} class in the i^{th} lithology related variable and w_i is the weight of the ith lithology related variable.

For the FRAME project, the map weight and the class weight are drived based on their subjectively of assessed favourability for indicating potential for the occurrences of a target deposit-type, all pattern in a lithology predictor map are ranked in the scale of 1 to 10. The most favourable lithology is ranked 10, whereas the least favourable lithology ranked 1. In this regard, the rank of a lithology is its class weight. Another predictor map used in this method is density of occurrences and this map also ranked based on the concentration of occurrences and ranked in the scale of 1 to 10. We consider lower rank (below 5) represent or insignificant importance and those lithology is not important as indicating potential for mineral occurrence.

In summary, generated fuzzy predictor patterns are based on (a) knowledge-based fuzzy membership values and (b) data-based conditional probabilities applied to a comparison of the results. The following flowchart shows how lithology map of Europe and mineralization/occurrences on a specific commodity have been used in to the favourability map produced by this method (Figure 22).

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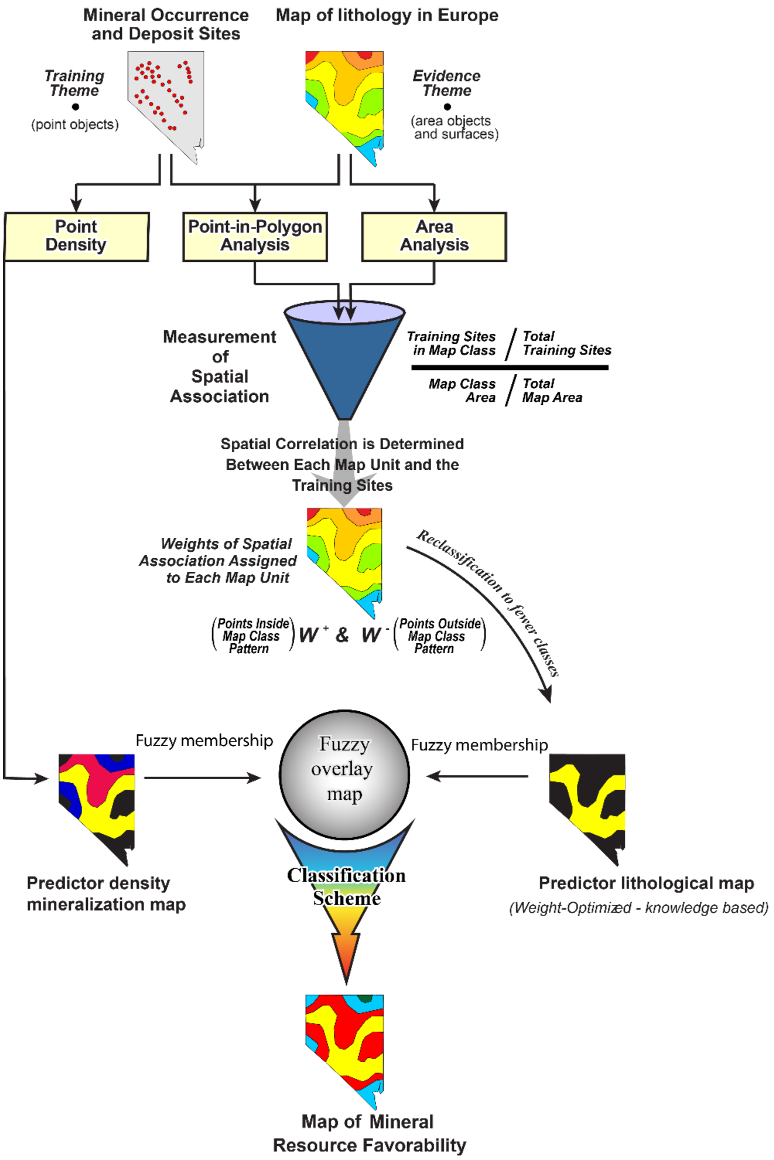

Figure 22 - Flow chart illustrating Hybrid Fuzzy Weigh of Evidence modelling method (modified after Mihalasky (2006) .

4.3 An example of hybrid Fuzzy-Wofe favourability map

Figure 23 shows a favourability map on lithium based on hybrid fuzzy-weight of evidence and the results of this method at the scale of Europe highlight several areas where nicely fit with the metallogenic areas on lithium previously presented by the work packages 3 and 5 in respective deliverable reports (Sadeghi et al., 2020, Gautneb et al., 2020).

The result of this prospectivity map highlight magmatic and magmatic-hydrothermal lithium mineralisations form numerous provinces that are mainly associated with two important orogenies: the Svecofennian and the Variscan as well as sedimentary-hydrothermal provinces which are hosted in more recent terranes. Lithium provinces associated to rare element granites highlighted in the Audierne bay rare element granite province and lithium associated with greinsen shows in the favourability map (e.g. Erzgebirge province). Sedimentary hydrothermal lithium mineralisation in the Jadar province also ranked with very high to high favourability in this map (Figure 23). The most favourable area in the Scandinavian are associated with granite- pegmatite (e.g. Västernorrland pegmatite province, Setesdal-Bamble-Nissedal pegmatite provinces, Kaustinen pegmatite province). Another provinces with high favourability for the lithium are in Galicia - Centro-Iberian pegmatite province, Somero-Tammela pegmatite province, Dobra pegmatite province, Shevchenkivske pegmatite province, Ambazac-Creuse-Millevaches province, Leon pegmatite province, South Brittany pegmatite province, Sudetes pegmatite province, Saxo-Thuringian pegmatite province.

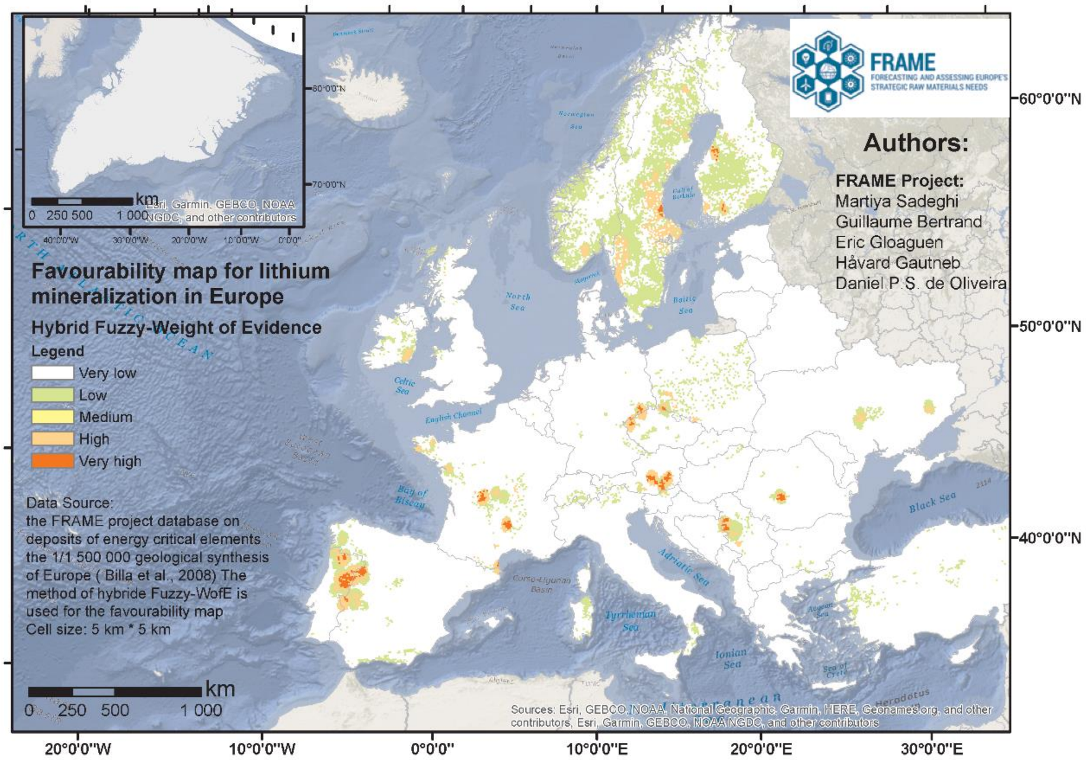

Figure 23 - An example of favourability map of lithium in Europe produced by Hybrid Fuzzy Weigh of Evidence modelling method.

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4.4 Discussion

It is interesting to compare prospectivity maps calculated with different methods, in order to identify their similarities, differences and therefore their strengths and weaknesses. In this regard, comparing the hybrid fuzzy WofE (Figure 23) and the CBA (Figure 8) prospectivity maps for lithium brings important information.

Overall, the two maps highlight relatively similar favourable regions areas that are western Sweden, southern Finland, the variscan segments of western Europe in Iberia, France and Czech Republic, essentially, and the eastern Alpine segment in Austria. But this is a first order observation. When comparing the two maps more thoroughly, it appears that they display significant differences.

The first difference lies in the coverage of the favourable areas. This of course might be an artefact of display, depending on the classification and symbology of results. Still, the CBA map displays much larger areas, while the ybrid fuzzy WofE map seems to better focus the favourability. This does not result from the scale of the input data, as the CBA map used a 1 to 1.5 million geological map of Europe versus a 1 to 5 million geological map for the hybrid fuzzy WofE map. A reason for this difference may reside in the methods themselves: CBA is a purely data-driven method while the hybrid fuzzy WofE method includes some expert guidance. An expert guided approach will search for a specific knowledge that comes form the expertise of the user (or operator) while a purely data-driven approach will have no pre-defined view and is based only on knowledge derived from the input data. In that sense, the data-driven approach is more neutral and objective, but can yield resultas that hardly make sense in a geological or metallogenic point of view.

The second difference is that the hybrid fuzzy WofE map seems to better mimic the main metallogenic provinces for lithium in Europe. This also probably results from the part of expertise that is included in the hybrid fuzzy WofE approach: the model will be keener to find known metallogenic areas as it is fed with expertise derived from them. On the other hand, data-driven methods like the CBA will “learn” from input data, is more likely to highlight areas corresponding to unexpected data association (i.e. that, for instance, could correspond to poorly studied mineral systems).

This of course should be further studied with more thorough and quantitative benchamarking, but it already supports the pertinence of both methods for mineral prospectivity mapping at continental scale: the partly expert-guided hybrid fuzzy WofE highlights areas that are favourable for known deposit types (corresponding to known and widely accepted exploration criteria) and is more discriminant than de data-driven

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CBA. On the other hand, the CBA is less discriminant but allows to highlight unexpected areas, such as Corsica and Calabria, for instance, for lithium. This in turn imposes to confirm the potential of these areas by further studies.

Finaly, a last point resides in the CBA method itself that considers geological environments and therefore downgrades the resolution of input data. For the CBA maps produced in the FRAME project, we have used cells of 100 km2 (10 x 10 km), which is a much lower resolution than the input geological map on which the favourability is based. However, this is a point that is currently being improved, with the development a new CBA method that replaces grid cells by overlapping search circles (Vella et al., 2021), amongst other improvements.

5 Conclusion

The present report describes the mineral prospectivity maps that were produced by the work package (WP) 3 of the FRAME project. These prospectivity maps assess the favourability in Europe, at continantal scale, for lithium, cobalt, natural graphite, phosphate, niobium, tantalum and rare earth elements. They are based on datasets produced by the FRAME project (WP4 for phosphate, WP5 for lithium, cobalt and graphite, and WP6 for niobium and tantalum) and by the former EURARE project for rare earth elements.

Favourability scores were calculated with the CBA (Cell Based Association; Tourlière et al., 2015) data-driven method that was developped especially for mineral prospectivity mapping at regional and continental scale, and with the 1 to 1.5 M geological map of Europe (Billa et al., 2008). The CBA method was improved during this work. These improvements include i) the addition of buffers around known deposits to identify lithological associations they are related too, and ii) a statistical testing and evaluation of several favourability scoring methods, in order to identify and select the most performant one for each dataset.

The main outputs of this work are the prospectivity maps at European scale for lithium, cobalt, natural graphite, phosphate, niobium, tantalum and rare earth elements presented hereabove. These maps are important tools to help assessing the favourability and potential for critical raw materials primary resources across Europe. In that sense, they constitute a significant step towards a better understanding and assessment of the primary raw material potential in Europe. They highlight areas that are known for their geological potential for CRM in Europe, such as the Variscan and Alpine belts for lithium,

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for instance, but more importantly, they identify areas were no or few deposits are known. These underexplored areas might deserve closer attention to better assess their favourability and potential. In that sense, further developments of this work could be detailed metallogenic evaluation of the favourability results, and more focused prospectivity mapping, at regional scale for instance, of the most prospective areas, including diversified sources of data (such as geology, tectonic structures, geophysics, geochemistry, etc.).

One should keep in mind however that these prospectivity maps are based solely on geological information and that they are a first order assessments at continental scale. The reason is that the geological map is the only data source that is exhaustively and homogeneously covering the whole European continent. Consequently, they are first order assessments of the geological favourability for the commodities in scope, without any economical consideration. Still, they constitute a critical source of information, for public authorities' policy making, or to help target future exploration areas, for instance.

In addition, a test of combined data-driven and expert-guided mineral prospectivity mapping at contiental scale has been conducted, using a hybrid fuzzy weight of evidence approach. This test allowed i) to test an additional method for mineral prospectivity mapping at continental scale, and ii) to compare both CBA and hybrid fuzzy WofE methods and to ssess their respective strengths and weaknesses.

The seven CBA prospectivity maps presented and described in this report are freely accessible as information layers and downlodable as pdf documents in the online EGDI data platform. As a consequence, they will remain available and visible to all end users beyond the lifetime of the FRAME project.

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