



FRAME

FORECASTING AND ASSESSING EUROPE'S
STRATEGIC RAW MATERIALS NEEDS

DELIVERABLE D5.1.

Title **Provide mineral potential and prospectivity maps of key mineral provinces in Europe with deposits of, or potential for, energy critical elements (natural graphite, lithium, cobalt) in collaboration with WP 3**



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Executive summary

Purpose:

- a) Collect data on lithium, cobalt and graphite occurrences in Europe, using the available sources, and cooperation partners.
- b) Organize the collected data based on well established methods and maintaining a suitable and limited complexity.
- c) Deliver the data to WP3 to make prospectivity maps of Li, Co and graphite and for making and for other critical minerals in Europe
- d) Give a review of the prospective provinces for Li, Co and graphite in Europe

Methods:

From the project partner, MREG members and from a number of individuals the data on the mineral occurrences' lithium cobalt and graphite where collected. In addition to standard geographical information such as name and location, information on the individual occurrence's deposit group (genetic types), occurrence type and status. The genetic types are based on standard ore petrology, with a small adaptation to our specific need, the occurrences and status follow INSPIRE codes.

The project partners contributed with about 40% of the data, and the rest of the data where supplied from MREG and EGS members and from academia. A grand total of 1624 occurrences are recorded in our database.

Results:

Using the Cell Based Association (CBA) method prospective maps of the Li, Co and graphite where created. Input to the model was our distribution of occurrences and deposits and a pan European geological map. A number of prospective areas where identified that corresponds to the distribution of the known occurrences in addition several areas without any presently registered occurrence were identified.

Difficulties/short comings:

The INSPIRE code list for deposit types of mineral occurrences, do not include everything that is used in standard ore geology, nor does it have the complexity needed for WP5. This may prevent an optimal integration of the data and results but will hopefully be solved or bypassed before project end. The partners submitted data of very variable quality.



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Further work:

Present a review of the formation of lithium, cobalt and graphite occurrences D5.2.

Present a report on the occurrences of Li, Co and graphite in Europe D.5.3.

Present the final maps of Li, Co, and graphite in Europe



Introduction

For many years, Europe in general, and EU in particular has been largely dependent on imported raw materials that are essential for industrial sectors such as the auto industry, telecom, information technology, aerospace and defense among others. In a society where decarbonization will be an important task, industries that develop batteries, photovoltaic (PV) panels, wind turbines, hydrogen production and storage and products for electrical mobility, have an increased importance.

The European commission have during the last decade published several comprehensive reports describing critical raw materials (CRM) for Europe, the latest recently published in 2020 (European Commission, 2020c). A CRM is defined as: a raw material with both a high economic importance and situation where there can develop a supply risk, because world production is dominated by a small number of producing countries. For any other details related to CRM we refer to (European Commission, 2020a, 2020c, 2020d) and references therein.

In the transition towards electrical mobility and storage of energy from wind and PV, a set of energy critical elements (ECE) have particular importance. Fig. 1 show predicted increase in the consumption of Lithium (Li), Graphite, Cobalt (Co), Nickel (Ni) and Manganese (Mn) from 2030 to 2050 (European Commission, 2020b).

Europe has been the worlds dominating producer of several of these raw materials in the past and have geological settings in many places that favors the enrichment of lithium cobalt and graphite.

Work package 5 (WP5) of the FRAME project (de Oliveira et al., 2020) (www.lneg.pt/frame) within the GeoEra platform (www.geoera.eu) has as its main aim; firstly to generate and compile data on the occurrences and production of the energy critical elements Li, Co and graphite in order to provide to the basis for exploration, exploitation data for decision making. Secondly to contribute to new and improved data in European mineral intelligence portals.

In WP5, this is the first of 4 deliverables. D5.1. will aim to provide mineral potential and prospectivity maps of key mineral provinces in Europe with deposits of, or potential for, energy critical elements (natural graphite, lithium, cobalt) in collaboration with WP 3. Thus, the most important part of D5.1 is the deliverance of our compiled and systematized raw data in form of an excel file to wp3. In addition, we will describe our approach used in collecting occurrences information and emphasize the limitations.

Additional material consumption batteries, fuel cells, wind turbines and photovoltaics in
renewables and e-mobility only
in 2030/2050 compared to current EU consumption* of the material in all applications

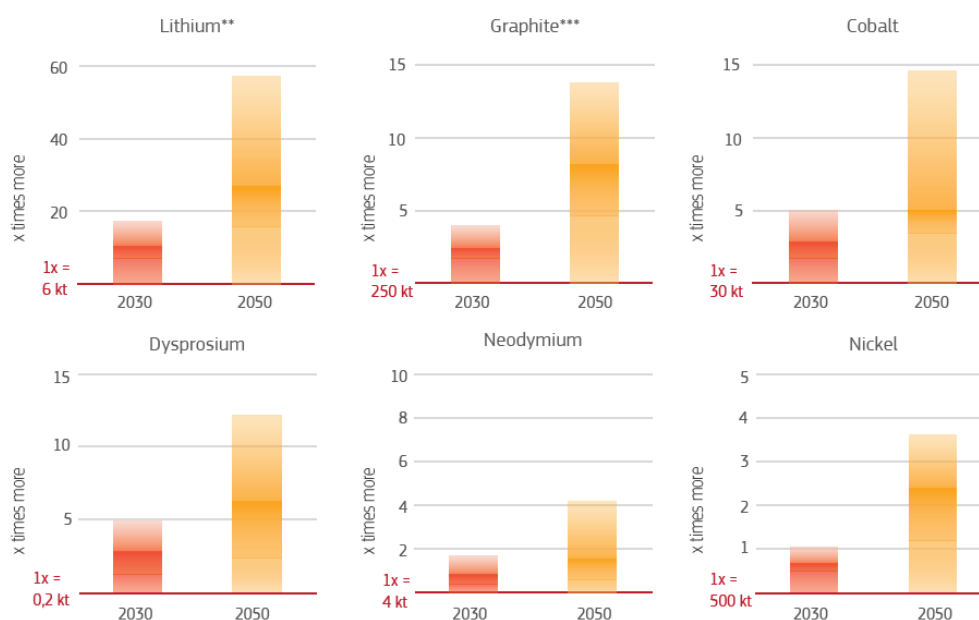


Figure 1. Forward looking expected consumption of ECE (European Commission, 2020b)

Project organization, materials and methods

Project partners and data suppliers

The scientific areas covering the geology of lithium, cobalt and graphite are so different that there does not exist any expert in Europe (perhaps not in the world) that will cover all these commodities with the scientific knowledge needed in GeoEra. At project planning stage it was decided to have three WP5 leaders, each covering the field of lithium, cobalt and graphite, with one of them acting as overall lead, responsible for coordinating the data collection and external communication. The WP5 leads with their respective field of expertise are:

Håvard Gautneb, NGU, graphite, overall lead.

Eric Gloaguen, BRGM, lithium,

Tuomo Törmänen, GTK, cobalt

At the startup of the GeoEra program, the WP5 of the FRAME project had 11 project partners. At the same time the European Commission had just started their “Battery action plan”(European Commission, 2019). FRAME and WP5 was asked to support DG GROW with basic information update on ECE elements (Li, Co and graphite). It became urgent and necessary that, if FRAME should support DG GROW and the commission with the needed information on ECE, data from the project partners only would not be representative. The

members of EuroGeoSurveys (EGS) Mineral Resource Expert group (MREG) where asked to supply data. Some individual researchers working on the same topic also supplied data to WP5. The contributors are listed in Table 1.

Table 1 List of Partners/countries, MREG members and individuals that delivered data to WP5.

Institution	Country	
Project partners		
CGS	Czech Republic	
GTK	Finland	
BRGM	France	
GSI	Ireland	
NGU	Norway	
LNEG	Portugal	
IGR	Romania	
GeoZs	Slovenia	
IGME	Spain	
SGU	Sweden	
GeoInform	Ukraine	
MEREG members*		
BGS	Great Britain	
BGR	Germany	
PGI-NRI	Poland	
	Slovakia	
RBINS	Belgium	Data from B. Gourcerol
	Bosnia-Herzegovina	Data from BRGM
	Serbia	Data from BRGM
HGI-CGS	Croatia	
IGMEgr	Greece	
IGR	Romania	
	Switzerland	Data from BRGM
ISPRA	Italy	
Individual contributors		
Manuel Scharrer	Germany	Univ of Tübingen
Stefan Horn	Great Britain	BGS
Blandine Gourcerol	France	BRGM

* Mineral resources expert group of the Eurogeoseveys.

The contribution from MREG members and the individual contributors had a great impact on the amount of raw data available for the work package. Fig. 2 and 3 show the impact of data from outside the project had on the available information

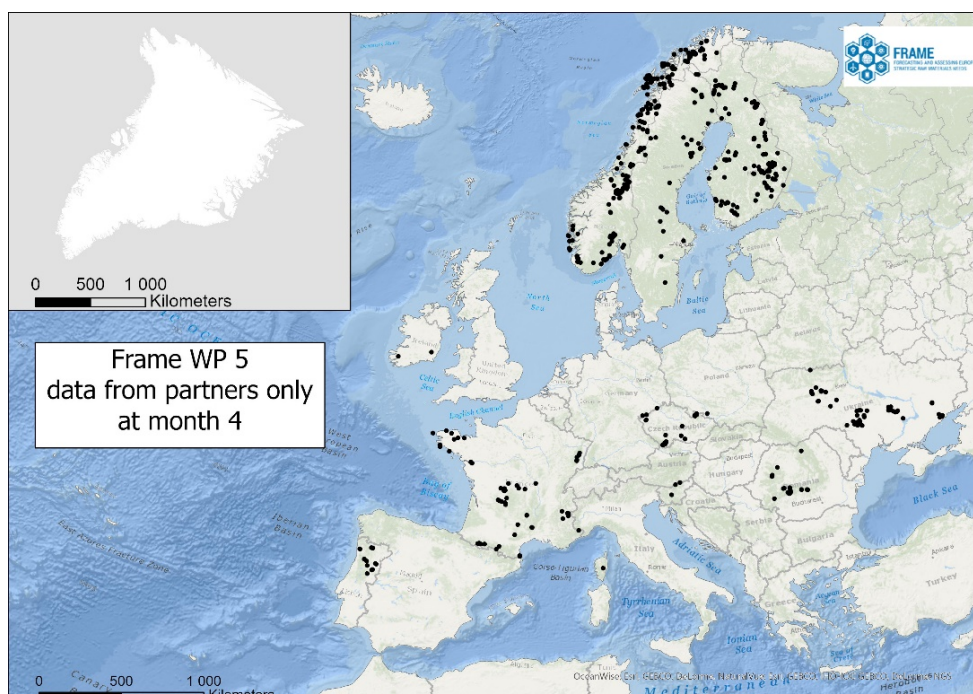


Figure 2 Plot of data at month 4 of the project.

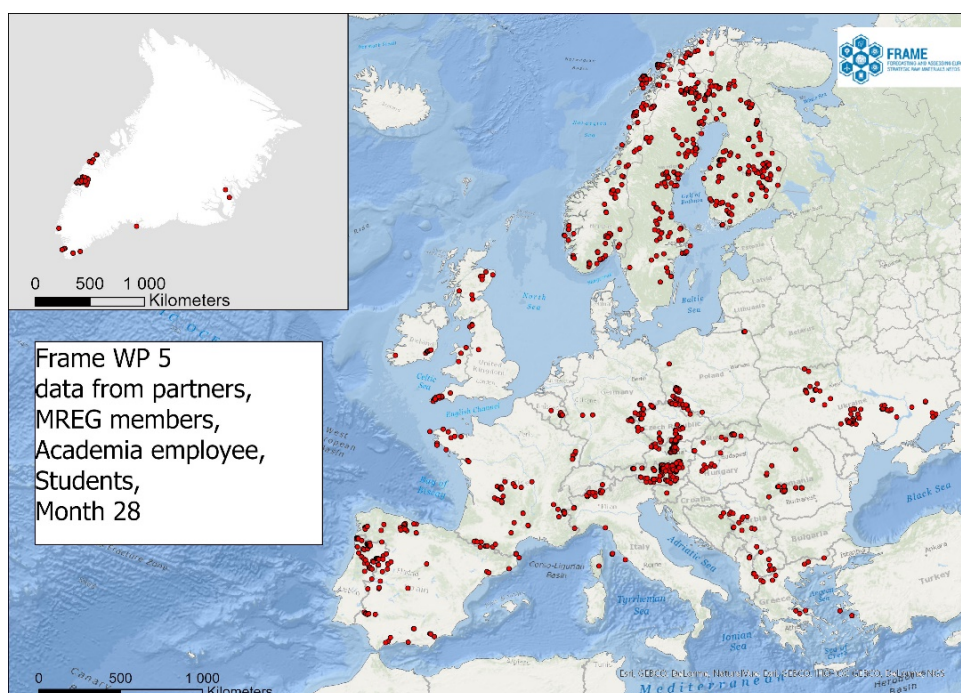


Figure 3 Map showing an about 60% increase in data, when contributions from sources outside the project are included (M28)

Figures 2 and 3 clearly show that without the additional data from contributors that are not members of the project, the overview of ECE presented below would not have been representative. It also shows that the data presented at the Minerals4EU web server is (<http://www.minerals4eu.eu/>) not representative.

Data collection

The WP leads decided at project start that to be able to quickly come up data that would answer DG GROW's request for information and make the gathering of information, quick and easy for the contributors, we had to request what is minimum to fulfill our tasks

The following information was requested from the partners and other data suppliers (Table 2).

Table 2 Data requested for the occurrences of Li, Co and graphite in Europe.

Data field	Field values		
Id			
Deposit name			
Country name			
Element	Li, cobalt, graphite		
Genetic type	See table 3		
Genetic sub type	See table 3	Only for Li	
Latitude	Decimal degrees		
Longitude	Decimal degrees		
Status	Active, closed, not exploited, Active, no Co production*.		
Occurrences type**	Occurrence, Prospect, Deposit Mine Tailing		

* This term is used for active mines, that produce a companion element usually Ni, but where Co presently is not a by-product

** Here we follow the INSPIRE definitions which in a simplified form can be defined as:

- Occurrence: Locality with an enrichment of a component above normal values.
- Deposit: Locality with an enrichment of a component above normal values, that also usually has a grade and tonnage estimated. This estimation can be compliant with international standards like PERC, JORC or UNFC, or noncompliant. The grade and tonnage information can be confidential.
- Prospect: Locality with an enrichment of a component above normal values, that lack the grade and tonnage estimate, but have a defined areal extent.
- Mine tailing represents an anthropogenic locality that can be occurrence or deposit

Many elements occur as accompanying elements and are only produced as a by-product when there is production of the main elements. Many elements are also enriched in nature by different geological processes, creating a large number of complex genetic types and ore forming processes. This is particularly the case for lithium and cobalt. For Co we regard any deposit with more than 100 ppm Co as a potential resource. This cut-off value was used with some difference between the various partners. In Norway for instance this cut-off was set to 300 ppm Co, to exclude a number of minor occurrences, taking care that that clusters remain to define prospective areas

Deposit ore types

The depots group types of lithium, cobalt and graphite used by WP 5 is listed in Table 3 For details see for instance (Beyssac & Rumble, 2014; London, 2018; Robb, 2020). They try to follow in a modified and simplified form what is standard in most textbooks of ore petrology eg.(Robb, 2020; Stanton, 1972)

Table 3 Deposit types (genetic types), and sub types for Li, Cobalt and graphite.

Li main genetic types	Lithium sub genetic types	Cobalt	Graphite
Brines	Pegmatite-aplite	5-element vein type	Graphite (amorph)
Greisen	Mixed NYF-Li (Pegmatite-aplite)	Black schist	Graphite (flake)
Pegmatite-aplite	Pegmatite-aplite	IOCG	Graphite (unclassified)
Rare element granite	Quartz-montebasite veins	Laterite	
Sedimentary-hydrothermal	Rare element granite	Magmatic Fe-Ti-V	
	Rare element granite	Magmatic hydrothermal	
	Unclassified	Magmatic Ni-Cu-Co	
	Sedimentary-hydrothermal	Metamorphic	
	Bauxite deposit	Orogenic Au	
	Cookeite occurrence	Sediment hosted Cu-Co	
	Lacustrine deposit	Sulfarsenides	
	Mn-(Fe) deposit	Unclassified	
	MVT deposit	Vein type	
	Sedimentary-hydrothermal	VMS deposit	

The data fields in table 2 and 3 were compiled in an aggregated in excel-sheets together with each contributor's data deliverable. This data is again basis for our discussions and various maps, see below. It also became apparent that the M4EU/Inspire code list for genetic ore types are not diverse enough for the complexity that is needed for Li, Co and graphite deposits. This is illustrated in appendix 1.

Overview of data

All together our database consists of 1624 occurrences/deposits that are distributed in the European countries as shown in Table 4.

Table 4 The number of occurrences per country and element.

Country/element	N	Country/element	N
Albania	9	Norway	159
Co	9	Co	85
Austria	298	Graphite	59
Co	16	Li	15
Graphite	232	Poland	43
Li	50	Co	32
Belgium	8	Li	11
Li	8	Portugal	209
Bosnia and Herzegovina	3	Graphite	4
Co	2	Li	205
Li	1	Romania	28
Czech Republic	43	Co	13
Co	4	Graphite	10
Graphite	7	Li	5
Li	32	Serbia	13
Finland	166	Co	5
Co	123	Li	8
Graphite	11	Slovakia	13
Li	32	Co	6
France	76	Graphite	1
Co	18	Li	6
Graphite	15	Slovenia	3
Li	43	Graphite	2
Germany	21	Li	1
Graphite	1	Spain	131
Li	20	Co	34
Greece	11	Graphite	30
Co	5	Li	67
Graphite	2	Sweden	166
Li	4	Co	63
Greenland	82	Graphite	75
Co	70	Li	28
Graphite	9	Switzerland	2
Li	3	Li	2
Hungary	8	Ukraine	64
Li	8	Co	16
Ireland	11	Graphite	35
Co	1	Li	13
Li	10	United Kingdom	29
Italy	21	Co	18
Co	4	Li	11
Graphite	3	Grand Total	1624
Li	14		
Kosovo	2		
Co	2		
North Macedonia	5		
Co	4		
Li	1		

Overview of mineralisation types

Lithium

Lithium is a very light metallic element, half as dense as water (density 0.53 Kg/m³), and which has high electronegativity (0.98). Under its metallic form, it is a soft metal with a low melting temperature (180.5°C). The abundance of lithium in the upper crust is about 0.002%. Its usages are very diverse, dominated since 2015 by the rechargeable battery sector according to (Kavanagh, Keohane, Garcia Cabellos, Lloyd, & Cleary, 2018). The challenges of the lithium market relate to extremely strong growth prospects. The main driver is the consumption of lithium intended for rechargeable lithium-ion batteries for the very rapid development of electro mobility and energy storage. Total lithium consumption has doubled in 10 years. Today, the main sector driving the sale of these lithium batteries is the production of electric vehicles and this situation should last for more than 10 years before a possible technological breakthrough for lithium-free batteries.

In order to produce high-purity lithium, **two distinct deposit types** are identified and defined as **conventional Lithium deposits** (Table 1). They are:

1) **brine deposits** hosted by salars eg. (Munk et al., 2016), in which the Lithium is under the ionic form, dissolved in brines at a grade of about 0.1% Li₂O; **Li-bearing brines are not considered in this study that focuses on Li-bearing hard rocks only. Nevertheless, one occurrence in the dataset is registered as a brine occurrence, related to the Zechstein salt in Poland.**

2) **hard-rock deposits** where the lithium is hosted by various Li-bearing minerals (Christmann, Gloaguen, Labbé, Melleton, & Piantone, 2015; Gourcerol, Gloaguen, Melleton, Tuduri, & Galiegue, 2019; Kesler et al., 2012) with a lithium grade that generally varies from ca 0.6 to ca 1.0% Li₂O. To date only, spodumene-bearing pegmatites are exploited to produce battery grade lithium. Presently, only the mineral processing of spodumene (Li-pyroxene) is economically profitable to produce high-purity lithium. Although, several mineral processes are under development for others Li-rich minerals, such as zinnwaldite, lepidolite and jadarite.

A second group of deposits is named **unconventional Li-deposit types** (Table1). This group encompasses a wide range of lithium mineralization, from various hard-rocks types to seawater, geothermal and oilfield brines. These unconventional Li-deposit types can be divided into 3 main groups (Table 1):

- 1) **Magmatic Li-mineralisation** that include other types of **Lithium-rich pegmatites** (Li-carrier = Petalite, lepidolite) and **high-phosphorus rare-element granites** (Li-carrier = lepidolite, amblygonite);
- 2) **Magmatic-hydrothermal Li-mineralisation**, where the economic grade is reached by two superimposed processes, magmatic then hydrothermal, which are typically represented by **Li-rich greisens** developed within rare-element granites or greisens within Li-bearing pegmatites;
- 3) **Sedimentary-hydrothermal Li-mineralisation**, where the economic grade is a conjunction of complex and imbricated processes, for example encountered in

volcanic settings (Volcanic caldera filled by volcanic and clastic sediments percolated by hydrothermal fluid flows), including frequently an important role played by the arid climate to form Li-bearing evaporates and/or supergene enrichments. Geothermal and oilfield brines localized in such environments are frequently rich in lithium.

For the needs of the FRAME project, the Lithium mineralization have been classified in 5 main types according to the available dataset and the INSPIRE deposit types codelist: 1) Pegmatite-aplite; 2) Rare-element granite; 3) Greisen; 4) Sedimentary Hydrothermal (including one brine occurrence in Poland) and 5) Unclassified.

A short description of these types is given below.

Pegmatite-aplites

According to (London, 2008), pegmatites are essentially igneous rocks, commonly of granitic composition that are characterised by their extremely coarse but variable grain-size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth-habits. Pegmatites occur as sharply bounded homogeneous to zoned bodies within igneous or metamorphic host-rocks. It should be added to this definition that pegmatites are relatively small-sized¹ (a few m³ to <0.5 km³), coarse-grained and/or aplitic igneous rocks of granitic composition occur as clusters of several bodies that constitute fields of pegmatites frequently over one thousand of individual bodies (A. Müller, Romer, & Pedersen, 2017). The pegmatite emplacement appears most of the time controlled by the structural (i.e. deformation) context eg. (Bhatt, Rana, Lahiri, & Mamtani, 2019; Butler & Torvela, 2018; Demartis et al., 2011; Deveaud, Gumiaux, Gloaguen, & Branquet, 2013; Silva et al., 2018) and the spatial link between faults and pegmatite is frequently highlighted (Deveaud et al., 2013; Silva et al., 2018). Among the classification of pegmatites (Cerny, Blevin, Cuney, & London, 2005) only the rare element Li subclass of the lithium-cesium-tantalum pegmatite family contains lithium mineralization. The highest lithium concentration is observed in the rare element Li complex and albite-spodumene types. These types of pegmatites are mainly encountered in continental collision orogenic setting (e.g. Variscan orogeny). The complex subclass includes 5 subtypes of diversely enriched pegmatites according to lithium-carrier (spodumene, petalite, lepidolite, elbaite, amblygonite). The Li₂O content varies as a function of the LCT pegmatite subtype and the Li-bearing minerals themselves, ranging from 0.5 to 1.5% (Gourcerol et al., 2019). LCT pegmatites show heterogeneous textures and compositions, and are composed of variable amounts of quartz, plagioclase, potassium feldspar, micas, with various amounts of garnet, tourmaline, apatite and accessory Li-bearing minerals – locally rock-forming – such as spodumene, petalite, etc. (see above). Although not systematically observed, LCT pegmatites generally show layering and/or concentric zoning.

¹ With the exception of some rare giant Precambrian pegmatites that reach the typical size of rare element granite

Table 5 Classification of lithium ore deposit types with ore minerals and mineralized examples. 1: Lepidolite refers to the Lepidolite compositional series, ranging from polyolithionite to trilithionite ; 2 : Zinnwaldite refers to the zinnwaldite compositional series.

		Magmatic		Magmatic-hydrothermal		Sedimentary-hydrothermal					
Conventional ore deposit (current reserves and resources)	Type	Spodumene-bearing pegmatites		–		Li-rich Salars					
	Ore mineral	Spodumene		–		Brine (Dissolved Li as LiCl)					
	Examples	Greenbushes (Australia), Manono (DR Congo), Whabouchi (Canada), Barroso (Portugal)		–		Atacama (Chile), del Hombre Muerto (Argentina)					
Unconventional ore deposit (some of current resources and possible future reserves)	Type	Petalite-Lepidolite ¹ pegmatites	High-Phosphorus Rare-element granites	Greisen developed in rare-element granite	Hydrothermal veins and alteration	Li-bearing clays associated to volcanism	Li-bearing oxides associated to Mn-(Fe)-rich sediments	Li-bearing clays & Li-bearing schists associated to evaporites	Jadar-type	Li-rich geothermal brine	Li-bearing bauxites
	Ore mineral	Petalite and/or Lepidolite ¹	Lepidolite ¹ , amblygonite-montebrasite	Zinnwaldite ² , Lepidolite ¹	Amblygonite, Tosudite / Li-rich muscovite, Lepidolite ¹ , zinnwaldite ²	Hectorite, Li-bearing smectites	Lithiophorite	Hectorite, cookeite	Jadarite	Li-rich Brine	Cookeite
	Examples	Lousas, Gonçalo (Portugal), Chedeville (France)	Beauvoir (France), Argemela (Portugal), Yichun (China)	Zinnwald (Germany), Cinovec (Czech republic), Chavence (France)	Takatama (Japan), Bekogorskoe (Russia), Le Châtelet (France), San José (Spain), Argemela mine (Portugal)	Clayton Valley (USA), Moldova Noua (Romania)	Drosgol (Scotland), Clews Gill (England)	Dauphiné black schists (France), Rhassoul (Marocco)	Jadar (Serbia)	Buntsandstein formation (Germany & France), Gwennap district (UK)	Dazhuyuan (China), Missouri state (USA)

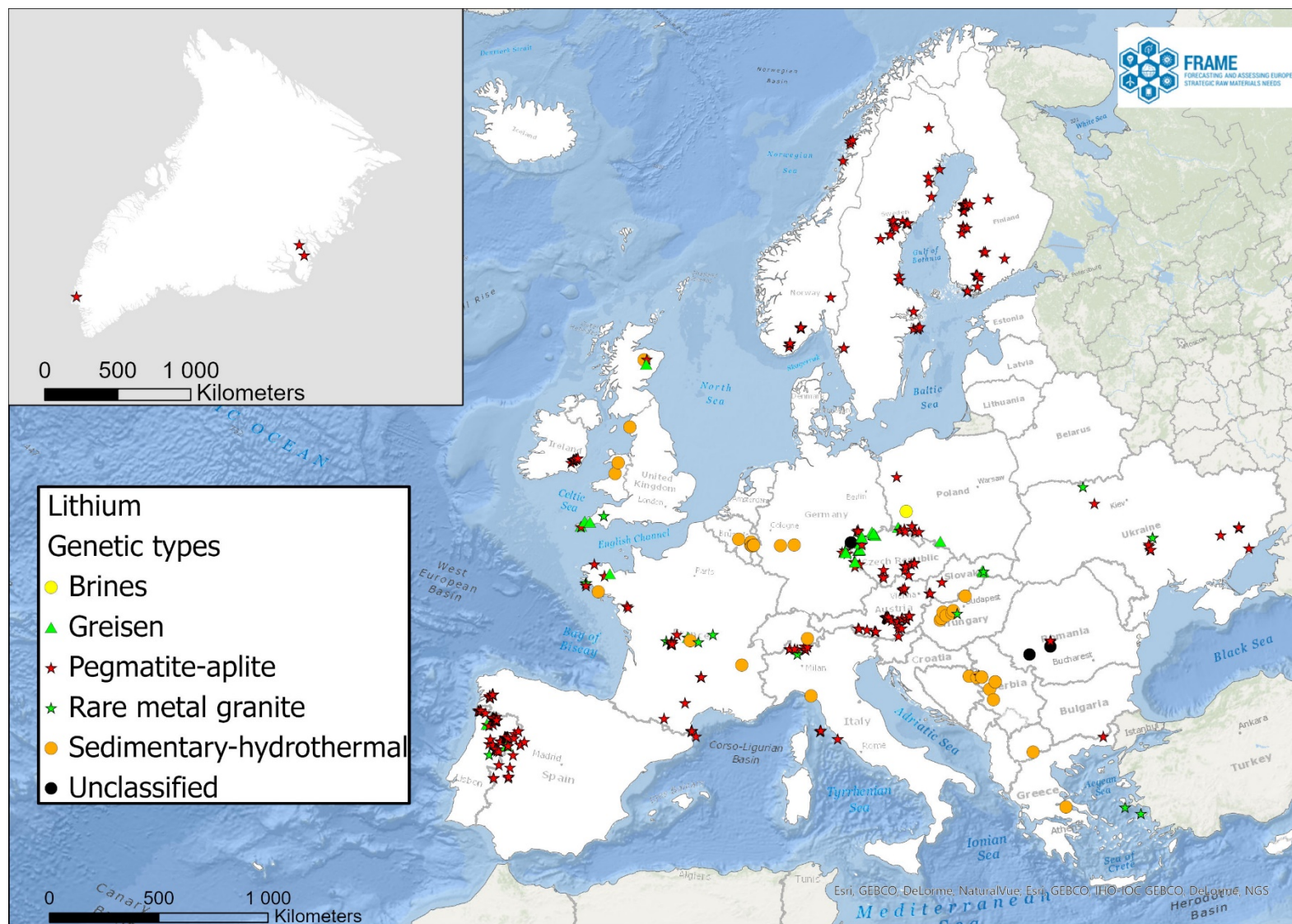


Figure 4 Genetic types (deposits groups) of Lithium deposits and occurrences.

This type of deposit is strongly interesting for its generally high-grade lithium content ($\geq 1\%$ Li_2O) and the associated high-value co-products (tantalum, tin). The main issue is related to the discovery of sufficiently large spodumene-bearing pegmatites (e.g. Sepeda pegmatite, Portugal) and the availability of a profitable mineral process to extract lithium from petalite, lepidolite or amblygonite, in order to produce high-grade lithium. Moreover, lithium-rich pegmatites are presently operated for the needs of the ceramic industry (e.g. Portugal).

Rare-element granite

The peraluminous, high-phosphorus class of rare-element granites (Cerny et al., 2005) are geochemically equivalent to the complex type of LCT pegmatites rare-element subclass. This class contains strong enrichments in lithium, tantalum and tin and variable enrichments in rubidium, cesium, beryllium and tungsten. The Li concentration is about 0.5 to 1% Li_2O , mostly hosted by micas (Lepidolite series and Li-rich muscovite) and phosphates (Montebrasite-Amblygonite series). These granites are rich in albite, poor in quartz and display frequent snowball quartz textures indicating a crystallization close to the surface (0-1000m). They contain disseminated magmatic cassiterite, rich in tantalum-niobium and sometimes in indium (Lerouge, Gloaguen, Wille, & Bailly, 2017), as well as columbite-tantalite and microlite that contain most of the tantalum and niobium. These rare-element granites, and their volcanic equivalents, occur as isolated small granitic bodies in continental collision orogenic setting (Gourcerol et al., 2019). They occur mostly close to the surface and are frequently spatially associated to and show strongly restricted volumes of magma, typically less than 1 km^3 .

This type of deposit is very interesting for its general high lithium content and the associated high-value co-products (tantalum, tin). The main issue is related to the availability of a profitable mineral process to extract lithium from lepidolite, to produce high-grade lithium. Moreover, most of the rare-element granites are presently operated for the needs of the ceramic industry.

Greisen

Greisen deposits result from a high-temperature hydrothermal dynamic alteration of magmatic potassium-felspar, plagioclase and biotite (if any) into a porous muscovite $\pm$ quartz assemblage generally located in the upper part of granite intrusion eg. (Launay et al., 2019; Pirajno, 1992; Štemprok, 1987). The greisen alteration occurs during the granite crystallization at depth and the magmatic fluids, both with external fluids, are responsible for the alteration in the upper parts of the intrusion. Thus, greisens are located along and close to the granite roof or along faults, veins and crosscutting dykes (pegmatites, granites). Greisens can occur as multi-stage swarms associated with Sn-W quartz veins (Černý, Blevin, Cuney, & London, 2005; Launay et al., 2019; Štemprok, 1987), or may form up to 100-m thick units with irregular to sheet-like bodies.

Peraluminous low-phosphorus to intermediate-phosphorus rare-element granites (Cerny et al., 2005) are favorable lithologies for the development of such deposit types, whereas geochemically less evolved granites appear to be unrelated with significant Li endowment. (Breiter et al., 2017) describe magmatic evolution of Cinovec rare-metal granite magmatic evolution of the late variscian volcano-plutonic system. The granite is slightly per aluminous, enriched F, Li, Rb, Cs, Nb, Ta, Nb, Sn, W, Sc and U. The granite cupola hosts greisen-type Sn-W-Li deposit with content of Li oscillating between 0,17 – 0.25 % (maximum 1,8 % Li). According to (Gourcerol et al., 2019) and references therein, the Li₂O content in the greisen around the world-class Panasqueira W deposit (Portugal) is only about 732 ppm, whereas Li₂O values from Li-rich greisens are in the range 80 - 3100 ppm. Greisens are mainly composed of Li-rich micas (muscovite, lepidolite, zinnwaldite) and quartz, with variable amounts of Li-phosphates (amblygonite-montebrasite series), cassiterite, wolframite, topaz, tourmaline, sericite and chlorite.

This type of deposit is very interesting for its generally huge lithium content and the associated high-value co-products (tantalum, tin, tungsten, scandium). The main issue is related to the availability of a profitable mineral process to extract lithium from zinnwaldite and lepidolite to produce high-grade lithium. High intensive magnetic separation (dry or wet) seems to be optimal for zinnwaldite separation.

Sedimentary-hydrothermal

This group encompasses various types and styles of lithium mineralization that results from various contributions of magmatism, fluid circulation, sedimentation sourced from Li-bearing rocks in closed or semi-closed basin. Contributions of arid climate conditions and/or surface weathering are also frequent. Recognized Li-mineralization are 1) Li-bearing clays (hectorite) associated to volcanism, 2) Li-bearing clays & schists associated to evaporitic sequence or arid sedimentary conditions, 3) Jadai-type, 4) Li-rich geothermal brine, 5) Li-bearing oxides associated to Mn-(Fe)-rich sediments and 6) Li-bearing bauxites.

The typical example of hectorite deposit is Clayton Valley (Nevada, USA). According to (Munk et al., 2016) and references enclosed, the Clayton valley is an arid closed basin surrounded by a basement including intrusive granites and a metamorphic core complex that in part controls the thickness of the basin via an important ductile to brittle normal fault. The felsic volcanism (rhyolites, silicic tuffs) located along the basin and interbedded within lacustrine sediment have Li₂O concentration as high as 491ppm. Alternating drying and wetting periods are responsible for the formation of lacustrine deposits and evaporitic beds. Hectorite in the surface playa sediments is rich in lithium (753 to 2521ppm Li₂O). Lithium-rich brines are also present in the basin. The lithium is supposed to come from the alteration of felsic volcanics by both magmatic and geothermal fluids as well from the surrounding basement, concentrated in the basin by evaporation.

Surficial processes related to weathering and climate may also concentrate lithium since Mn-Fe-rich sedimentary units (reddish siliciclastic rocks or Mn-Fe lenses and crusts) and

some primary to secondary bauxites contain frequently secondary Li-oxides such as lithiophorite (Lithium oxide with 3.16% Li_2O). In some bauxites, the Lithium content is up to 0.53% Li_2O e.g. China, (Wang et al., 2013) and Li-carrier are represented by lithiophorite, cookeite and tosudite.

Li-bearing clays and Jadar-type deposits are very interesting for their generally high-grade lithium content ($\geq 1\%$ Li_2O) and high tonnage of ore. Moreover, some associated co-products (borate) may add value to the deposits. The main issue is related to the availability of a profitable mineral process able to extract lithium from jadarite and/or hectorite to produce high-grade lithium.

Unclassified

Some Lithium occurrences provided by project partners do not contain attributes that are required to classify them. In these rare cases, Li occurrences are considered unclassified. Two secondary deposits are registered in Czech Republic. There are mining waste after tin and tungsten minerals separation from greisen ores



Cobalt

Cobalt is a metallic element with similar electrochemical properties to e.g. manganese, iron and nickel and can, therefore substitute these elements in many minerals. The average cobalt content of Earth's crust is 0.003 wt. % (or 30 parts per million, ppm), which is similar compared to other base metals (copper 0.0025 wt. %, nickel 0.0056 wt. % and zinc 0.0065 wt. %) (e.g. (S. R. Taylor & McLennan, 1995; Wedepohl, 1995) Similar to nickel, highest cobalt contents occur in MgO-rich mafic-ultramafic rocks (0.005-0.01 wt. %), whereas sedimentary and granitic rocks contain lower amounts of cobalt (0.002, and 0.0003 wt. %, respectively).

The application of cobalt can be divided onto two main group: Metallurgical and chemical. Metallurgical applications include alloys and carbides used in aerospace industry, cutting tools and magnets. Cobalt chemicals are used as catalysts, dyes and pigments. Increasingly, cobalt is used in rechargeable Li-ion batteries (LIB), as a cathode material. Cobalt is used in Lithium-Cobalt-Oxide (LCO), Lithium-Manganese-Oxide (LMO), and Lithium-Nickel-Manganese-Cobalt-Oxide (NMC), as well as nickel-cadmium and nickel-metal hydride batteries, accounting approximately 50 % of global use of Co.

Cobalt rarely form its own deposits, but it occurs as a minor constituent in a number of ore deposits types, typically with grades from 0.01 to 0.2 wt. %. Globally, the most important deposits are stratiform sediment-hosted Cu-Co deposits (or sedimentary rock - hosted stratiform Cu-Co deposits) eg (Murray Hitzman, Rodney Kirkham, David Broughton, Jon Thorson, & David Selley, 2005; Horn et al., 2020), which produce 63 % of world cobalt (mostly in DRC), followed by lateritic Ni-Co deposits (20 %) and magmatic Ni-Cu-(Co-PGE) deposits (14 %). In addition, cobalt occurs in a number of other deposits types, e.g. in some volcanogenic massive sulphide (VMS) deposits, iron oxide copper gold (IOCG) deposits, and certain Au(-Cu-Co) deposits. The so-called 5-element vein deposits and other vein type deposits (e.g. Bou Azzer, Morocco) are the only deposit type where cobalt can be the main commodity with percent-level concentrations (Mudd, Weng, Jowitt, Turnbull, & Graedel, 2013; Slack, Kimball, & Shedd, 2017).

Stratiform sediment-hosted Cu-Co (SSHC) deposits are fairly rare in Europe but the Mesozoic Kupferschiefer deposits can be classified as a SSH type deposits. Globally SSH deposit contain an average of 0.3 % Co, while DRC deposit contain typically 0.2-1 % Co (Slack et al., 2017; C. D. Taylor et al., 2013). In comparison, the Kupferschiefer contains only some 50-80 ppm of Co, but up to 140 ppm in the Lubin ore (Pazik, Chmielewski, Glass, & Kowalczyk, 2016). The main carriers for Co in DRC deposits are heterogenite (CoOOH) and carrolite (CuCo₂S₄), whereas in Kupferschiefer it is cobaltite (CoAsS) (Pazik et al., 2016; Roberts & Gunn, 2014). SSHC-type deposits are derived from hydrothermal fluids precipitating Cu and Co at the contacts of oxidised-reduced sedimentary strata (M Hitzman, R Kirkham, D Broughton, J Thorson, & D Selley, 2005).

Lateritic Ni-Co deposits are formed by weathering of bedrock in tropical to subtropical climates. They are deposits ranging in age from mid-Tertiary to recent. Nickel and cobalt laterite deposits are formed on top of mafic and especially ultramafic substrate, where they can contain $\geq 1\%$ Ni and 0.03-0.15 % Co. Three different sub-types of laterite deposits occur:

oxide, hydrous magnesium silicate, and clay silicate (e.g. Gleeson et al. 2003). Depending on the laterite type, Co can be hosted in a number of phases including silicates (serpentine, talc, chlorite), clays (nontronite, montmorillonite), oxides (heterogenite, asbolane), and also secondary formed sulphides (millerite, heazlewoodite) (Slack et al., 2017). Lateritic deposits in the Balkans and Greece are generally developed in Mesozoic- Cenozoic ophiolite belts and typically contain 0.04-0.06 % Co, the Brezik Tadići deposit in Bosnia-Herzegovina contains 0.1-0.38 % Co (Horn et al., 2020).

Cobalt is a ubiquitous minor constituent in **magmatic Ni-Cu(-Co-PGE) sulphide deposits**, hosted by mafic-ultramafic intrusions, dykes and lava flows (komatiites). Mineralisation types vary from generally low-grade disseminated deposits to more high-grade semi-massive and massive sulphide accumulations. Typical metal grades vary 0.5-5 % Ni, subequal amounts of Cu and 0.01-0.2 % Co (typically 0.01-0.07 %). As most of the Co is hosted by pentlandite, the main Ni-sulphide phase, there is a near linear correlation between Ni- and Co-grades. The most significant deposits in Europe generally occur in the Nordic countries, e.g. Kevitsa mine in Finland (2019 reserves and resources 277 Mt, 0.25 % Ni, 0.34 % Cu and 0.01 % Co (Co-head grade 0.012-0.015%) (Boliden, 2020), the past producing Aquablanca mine in Spain being most prominent example outside Fennoscandia (Slack et al., 2017).

Volcanogenic massive Cu-Zn sulphide deposits (VMS) represent accumulations of sulphides at or below sea floor, deposited by discharging hydrothermal fluids. Typically, they contain variable amounts of Cu, Zn, and Pb and they often contain also economic concentrations of Au and Ag. Generally, the cobalt-content of VMS deposits is low at a few hundred ppm's, but some deposit types can contain significant Co, such as the Outokumpu-type deposits in Finland, where Co grades typically 0.1-0.2 %. In addition, about 50 % of the cobalt is carried in discrete Co minerals, most often cobaltpentlandite, which made it possibly to produce a Co-concentrate. In most cases, the low Co-grade and the fact that it resides in multiple host minerals, including Fe-sulphides, hinder the production of any kind of Co-concentrate.

Co-bearing vein type deposits occur in several locations throughout Europe. They comprise the classic 5-element (Bi-Co-Ni-As-U-Ag) vein type deposits (e.g. Dobsina, Slovakia and Saint Marie Aux Mines, France), other vein deposits (e.g. Cornwall) and also sulfarsenide-type (e.g. Złoty Stok Poland). A typical feature of these deposits is the occurrence of Co-As-S minerals and some authors actually classify these deposits belonging to the same group of hydrothermal Co deposits (Horn et al., 2020; Scharrer, Kreissl, & Markl, 2019). Some **Iron-oxide Cu-Au (IOCG) deposits** in NW Finland and N Sweden contain low cobalt grades (100-200 ppm) but have relatively large contained Co tonnage, as some of these deposits are large tonnage such as the Hannukainen deposit in Finland (221 Mt). However, cobalt is typically contained Fe-sulphides (pyrite, pyrrhotite), most of which would be concentrated in tailings of Cu-Au flotation. **The black schist** hosted Talvivaara deposit in Finland represent a rare type of unusually base metal enriched black schist. This giant deposit has mineral reserves of 1500 Mt with an average Co grade of 190 ppm (Terrafame, 2018). Cobalt is hosted by pyrite, pyrrhotite, and pentlandite, where it is released by the bioheapleach process.

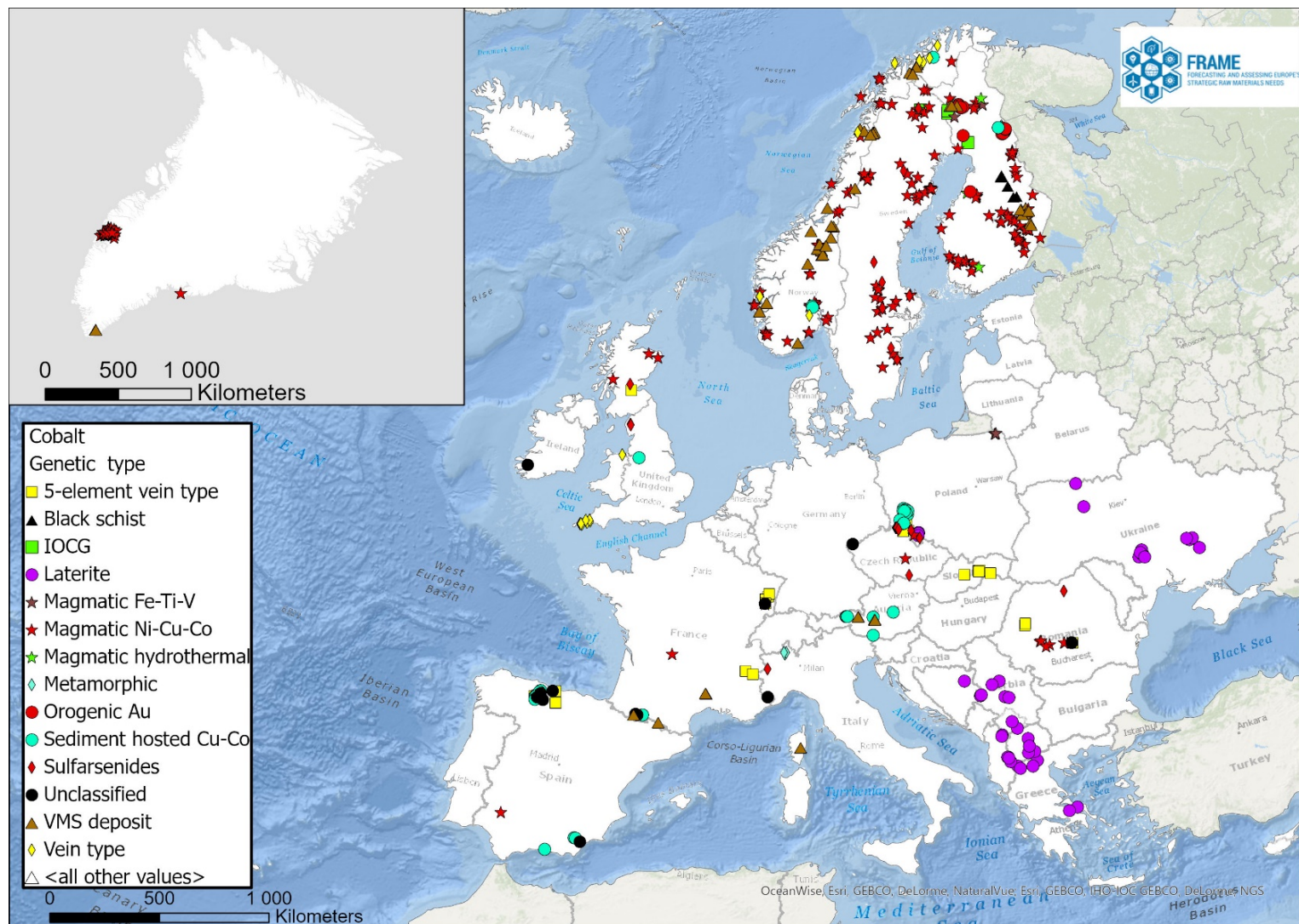


Figure 5 Genetic types (deposit groups) of cobalt deposits and occurrences.

Graphite

Graphite is relatively common mineral in meta-sedimentary rocks. However, it is rare to find graphite enriched and crystallised in an amount and form that is regarded as economically interesting. The number of registered occurrences of graphite in most countries are much lower than that of base metals for example, and in the literature the number of studies is few compared to other commodities. Graphite is an expensive commodity compared to other industrial minerals with a price that is in the order of 5 to 10 times more than for instance standard purity quartz, limestone and feldspar. In batteries graphite is used in the anode (during discharge, anode and cathode switch side when a battery is recharged) and usually used in amounts that is from 2-2.5 times higher in comparison to the amount of lithium. The main end use (about 50%) of graphite is to the refractory industry where graphite is used various steps of metal production, while only about 10% is used in battery production (European Commission, 2020d).

The scientific community classify organic matter relative to increasing degree of crystallographic ordering, into: **a) Natural char, b) Natural coke, c) Semi graphite and d) Graphite**. The methods and characteristics that distinguishes these variants have been described by (Kwiecińska & Petersen, 2004). The details regarding the differences is a topic for the deliverable D.5.2. To keep this report concise, we will not go into much details here other than to briefly describe the difference between graphite and semi-graphite. **Graphite** and **semi graphite** are distinguished that graphite have a d_{002} interlayer spacing of $3.3539 \pm 0.0001 \text{ \AA}$ and Semi-graphite have a d_{002} interlayer spacing of $3.38\text{-}3.37 \text{ \AA}$.

Somewhat simplified, most graphite occurrences are formed by the metamorphism of organic material. During the early stage of metamorphism volatiles like CO_2 , CH_4 and H_2O are released from the organic matter, reduction of these volatiles results in the formation of graphite. If this process take place in situ in the rock, flake graphite deposits will form, if the carbon is part of volatiles in a solution, the carbonaceous component may be deposited in veins, forming vein type of graphite deposits (Beyssac & Rumble, 2014; Buseck & Beyssac, 2014).

The industry classifies graphite, into **vein-, flake- and amorphous** graphite where the latter in most cases represent fine grained (<1 micrometer grain size) material of flake graphite. The industry grouping is also related to different end use for amorphous and flake graphite. Coarser grained flake graphite has different physical properties such as: thermal stability, heat conductivity, electrical conductivity among other. In Europe there are no active vein graphite mines at present, but vein graphite is found as geological curiosities several places (Luque et al., 2014)

It is not uncommon that single graphite deposits have parts that is regarded as flake and other parts that are classified amorphous, meaning that the grain size of graphite crystals can vary, often unsystematically over short distances. Such variation is believed to be related to several factors such as:

- a) Primary variation in the ratio between organic matter and gangue minerals
- b) Tectonic stress with deformation and grain size reduction.

- c) Several episodes of graphite crystal growth and recrystallization under different P-T conditions.

Vein type of graphite is described from several places in Europe, the most famous being the now exhausted Borrowdale of Cumbria in United Kingdom (Barrenechea et al., 2009), but vein deposits are described as geological curiosities at a couple of other places in Europe. (Luque et al., 2014). Since there is no deposit in EU of vein type graphite that is regarded as economical interesting or that is under exploration or development, at present this genetic type of graphite will not be discussed further here.



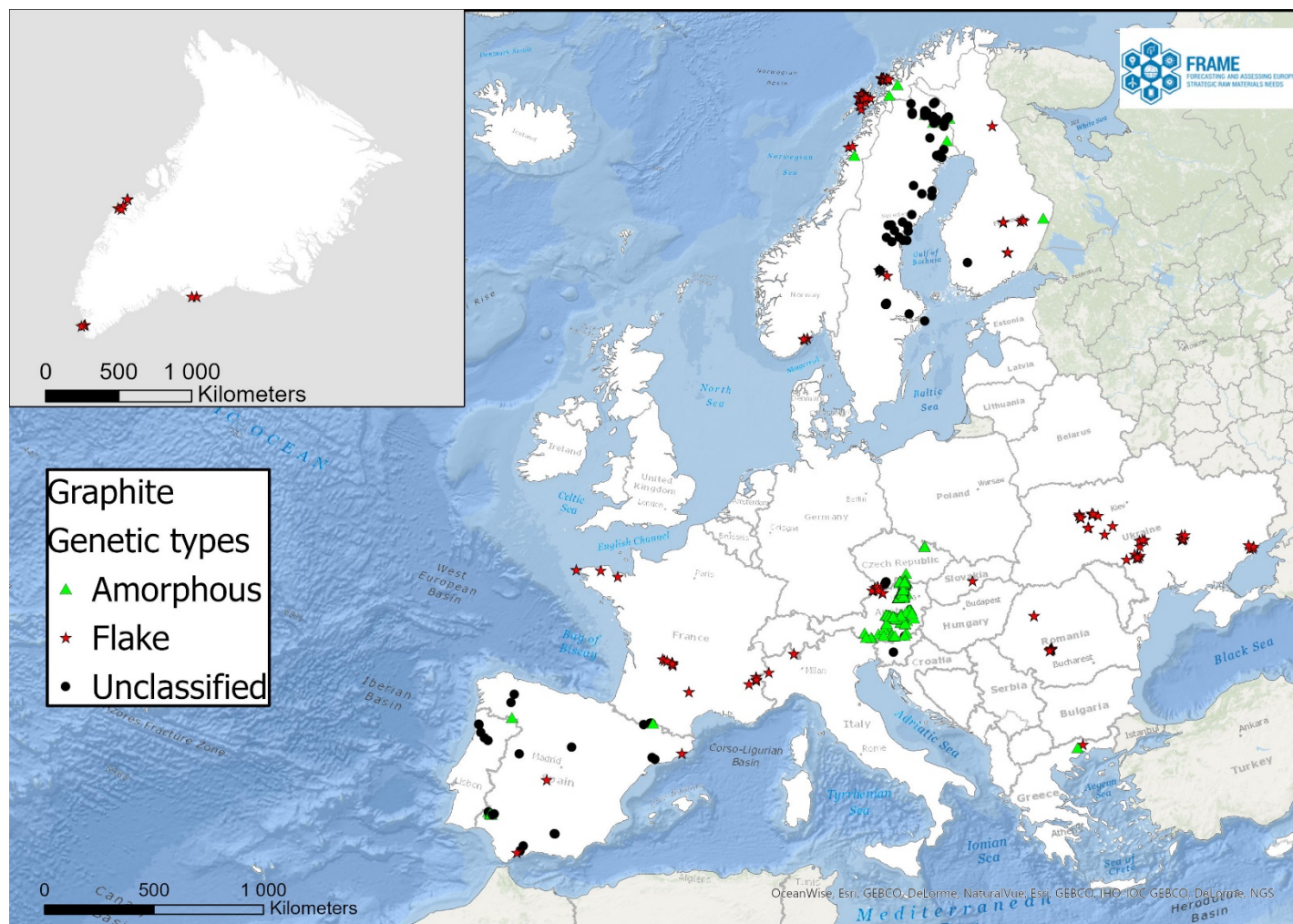


Figure 6 Genetic types of graphite deposits and occurrences.

Prospectivity maps

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 could be grouped in two categories, i) the “expert guided” methods that rely on the existing knowledge of experts to search for analogs, and ii) the “data driven” methods that rely on data processing to deduce “knowledge” that is then used to assess the favourable areas. Data driven methods largely progressed in the past decade with the tremendous development of computing capacities and databases.

When it comes to mineral prospectivity mapping at continental scales (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 Cell Based Association (CBA) – that has been recently developed by BRGM (Tourlière, Pakyuz-Charrier, Cassard, Barbanson, & Gumiaux, 2015).

Overview of the CBA method

Most data driven mineral prospectivity mapping methods are based on unequivocal relationships between points (known deposits) and the cartographic entities that contain them (pixels or polygons). This “shortcut” may lead to several issues that could significantly bias the results:

- Uncertainties in polygon contours and point location may result in wrong associations.
- Surface of polygons are often considered a relevant parameter for weighting, which 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 spatial distribution of points is often not considered, which may lead to the inappropriate generalization of a local feature to a whole formation.

A way to solve these issues is to consider the geological environment around known deposits and “learn” from this information to assess the favorability. We believe it is more appropriate than considering solely the “point-polygon” unequivocal link. The CBA method has been developed with this underlying base principle. Its application relies on a succession of relatively simple steps of data processing and calculation:

- The first step is to superimpose a regular grid (“cells”) over the area of study.
- The second step is to build an attribute table, 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, and then provides a “lithological spectrum” that describes the lithological associations in all cells.

- The third step is to identify the lithological associations related to known deposits (in circular buffers around deposits), that are considered favourable, and to compare them with lithological associations in the cells to assess their favourability.

For this work, we have tested several methods to score cells according to their similarity with favourable associations. We performed statistical tests to assess their performances. These tests and their results are described and discussed in deliverable D3.3 of the FRAME project. Basics of the CBA method are also described in details by (Tourlière et al., 2015).

CBA prospectivity maps

The CBA prospectivity maps were calculated with the FRAME database of energy critical elements compiled by WP 5 of the FRAME project (Figure 7), the 1 to 1.5 million geological map compiled by BRGM (Billa, Cassard, Deschamps, & Salpeteur, 2008) (Figure 8) and a regular grid of 10 by 10 km cell size. 10 by 10 km may seem rather coarse, but it is in the order of size of an exploration permit, and it was a good compromise between “geological reality” and “computing constraints”.

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 classification method (Jenks natural breaks of equal intervals), which has been chosen to ensure a proper visual variability of the results on the map.

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 to refine the CBA prospectivity mapping at regional scale, in favourable areas, with additional pertinent datasets.

FRAME DATABASE ON
ENERGY CRITICAL
ELEMENTS (Co, Li,
natural graphite)

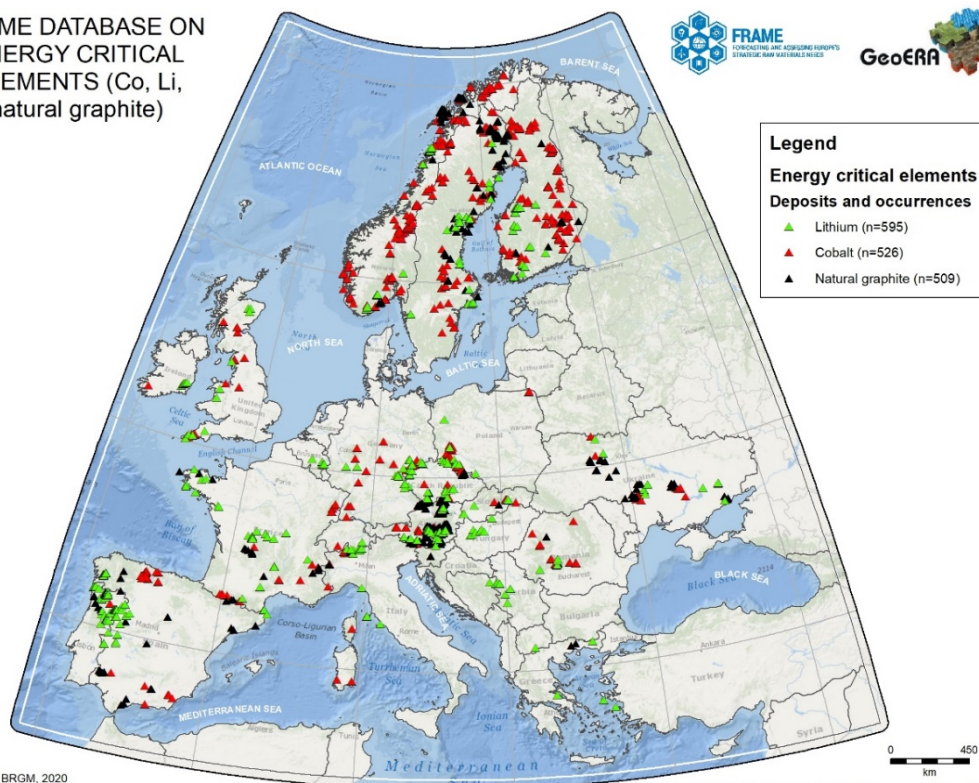
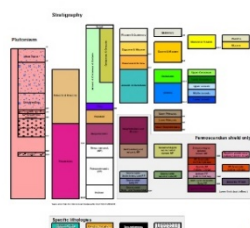


Figure 7 Dataset of energy critical elements (Li, Co and natural graphite) compiled by the WP5 of the FRAME project.

GEOLOGICAL MAP OF EUROPE
1 TO 1.5M SCALE



Billa M., Cassard D., Deschamps Y., Salpeteur I.
Europe Mineral Resources GIS. In 33rd
International Geological Congress,
Oslo, August 6-14th 2008

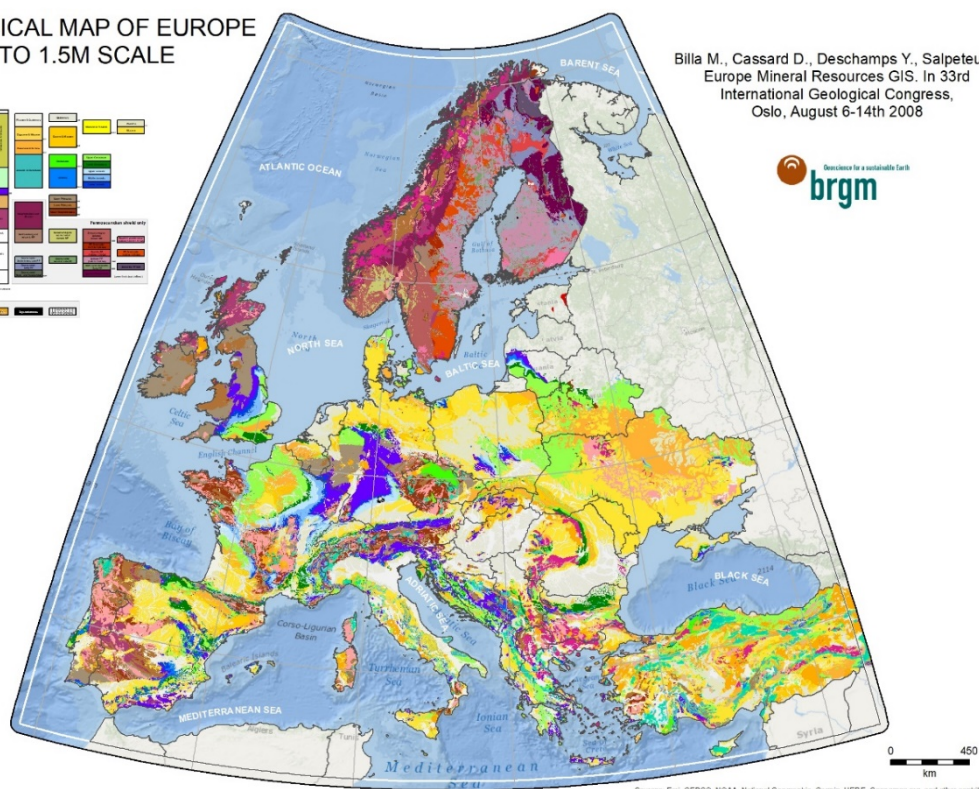


Figure 8 Overview of the 1 to 1.5 million geological map compiled by BRGM (Billa et al., 2008).

Lithium

The CBA favourability map for lithium (Figure 9) shows 3 highly favorable areas:

- ✓ The Svecofennian orogeny in south of Finland and east of Sweden;
- ✓ The Neoproterozoic to Paleozoic basement affected by the Variscan orogeny (Western Iberia, Variscan massifs from France, Bohemian massif) as well as late Carboniferous to Permian metamorphism and magmatism (East Austria, French Pyrenees, Corse);
- ✓ Pelagonian metamorphic massif and Neogene accretionary belts (Dinarides, Hellenides, etc.) from Slovakia to Bulgaria.

This is not surprising as numerous Li occurrences are known in these regions. What is probably more interesting is that the map shows very high favorability in areas where no (or few) occurrences from the input dataset exist. In details, these high favourability areas are located, for instance:

- In Galicia, in northwestern Spain,
- In Extremadura and Andalucia, in southwestern Spain,
- In the southern part of the Armorican massif in northwestern France,
- In Corsica,
- In Calabria in southern Italy,
- In the Vosges and Schwarzwald massifs near the French-German border,
- In the central part of Romania (South Carpathians,
- In the western part of Bulgaria.
- Austria?

These favorable 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.

Interestingly, even if lithium-brines have not been taken into account in this study, most of the known ones are localized in areas highlighted by mineral prospectivity. This is for example the case in the Vosges-Forêt Noire area (French-German boundary) where Li-rich geothermal brines are localized in the Eocene-Neogene Rhin graben. This underline the link between occurrence of Li-brines (geothermal or whatever) and a basement that contains some amounts of lithium.

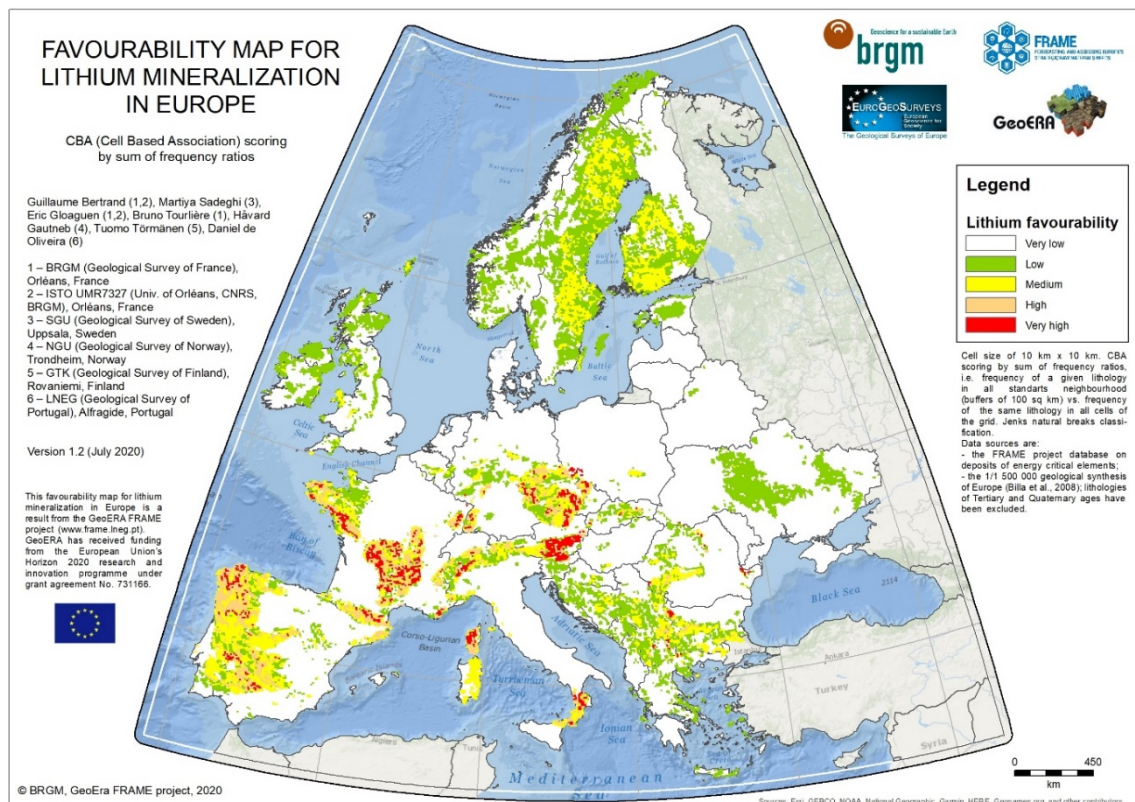


Figure 9 – CBA favourability map for lithium.

Cobalt

The CBA map for cobalt (Figure 10) highlights the high favorability of the Fennoscandian shield. This is again not surprising because lot of cobalt occurrences are known in this region. Still, a close study of favourability distribution might reveal prospective areas that should be given more interest in future exploration. In addition, the 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 the western Slovakia,
- In northern- and southernmost Finland,
- And in various other areas.

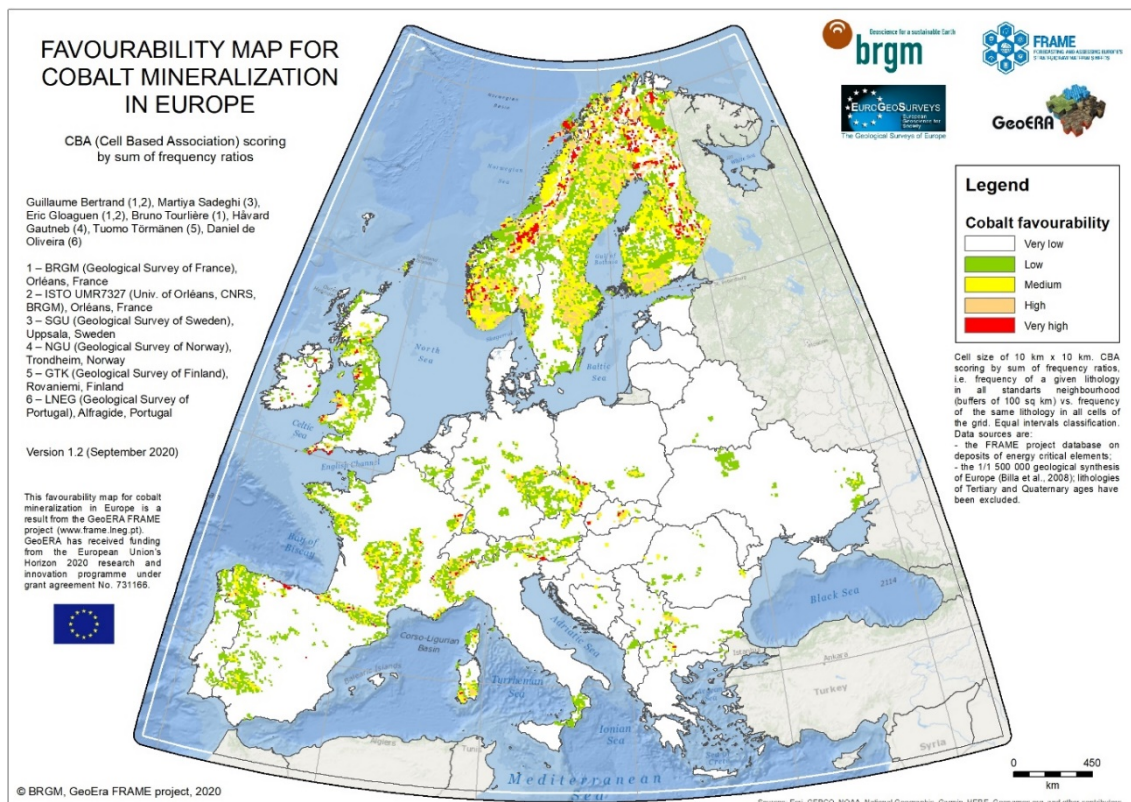


Figure 10 CBA favourability map for cobalt.

Natural graphite

The CBA map for graphite (Figure 11) shows very high favorability in the Lofoten Islands in Norway and in Austria, which again was expected as lot of graphite occurrences are 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 northwestern France,
- The western central massif in France,
- The Schwarzwald massif in southwestern Germany,
- The Bohemian Massif Czech Republic
- Central Slovakia,
- The southwestern part of Romania,
- The western and southern part of Bulgaria
- North Macedonia.

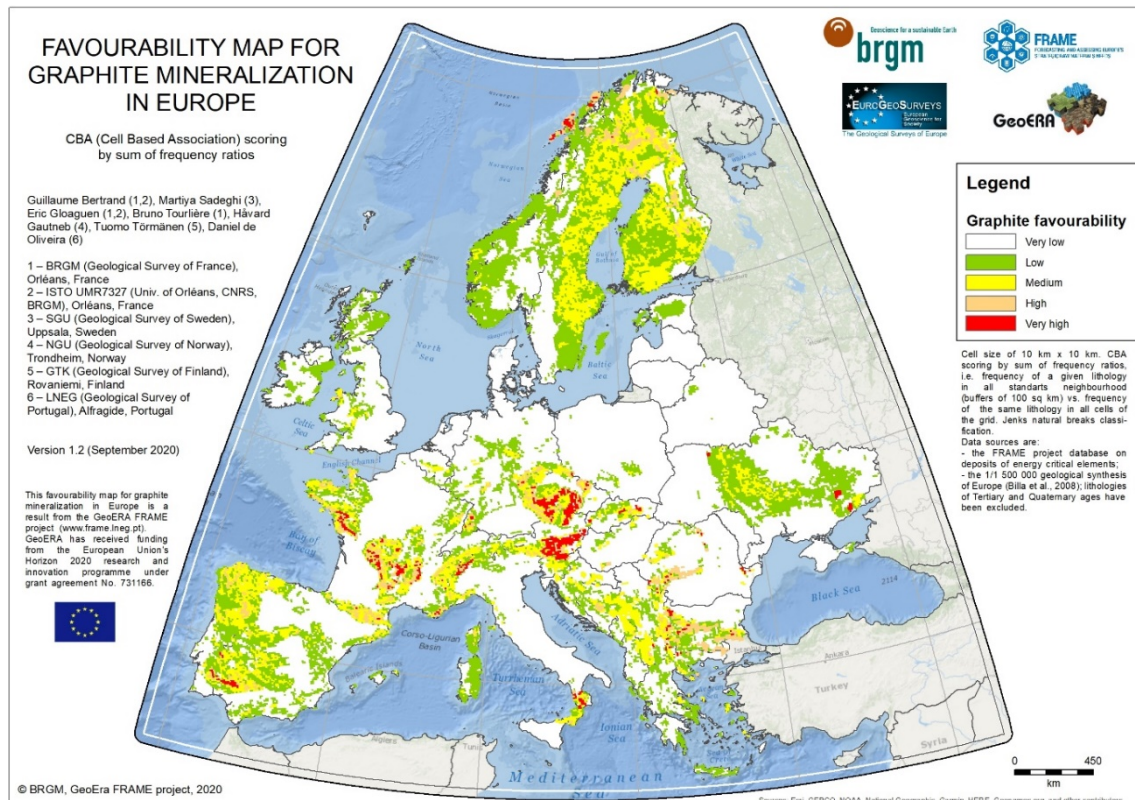


Figure 11 CBA favourability map for natural graphite.

It is important to note the favorability map for graphite do not distinguish between flake and amorphous graphite. In some areas both types occur together since amorphous and flake graphite are distinguished based on grain size and not on their petrogenetic processes of formation.

Conclusion

To conclude, we have to stress that that these prospectivity maps are based on geological features, so they provide a “geological favorability”. They do not consider economical aspects, and they do not presume the economic viability of any future discovery. Still, they highlight areas that are favorable for the discovery of new occurrences and hopefully new deposits.

Prospectivity maps highlight some areas where deposits are already known. That of course is not a novel result, but it somewhat confirms the reliability of the mineral prospectivity mapping approach. These favourable regions need anyway to be carefully scrutinized as it might appear that some prospective areas were given too little interest in the past.

In addition, these maps highlight favorable areas where no occurrences are reported in the input deposit datasets, and that is in our opinion an interesting output of this work. These prospective areas should be given a closer focus and studied in more details in further studies, eventually combining more diverse datasets (e.g. geophysics, geochemistry), to confirm their potential. As such, the present study opens new doors for future exploration works.

Keys mineral provinces

Lithium

Taking into account the results of both mineral prospectivity and the distribution of lithium deposits and occurrences, 25 metallogenic provinces have been defined (Table 6). Magmatic and magmatic-hydrothermal lithium mineralisations form numerous provinces that are mainly associated with two important orogenies: the Svecofennian and the Variscan. 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).

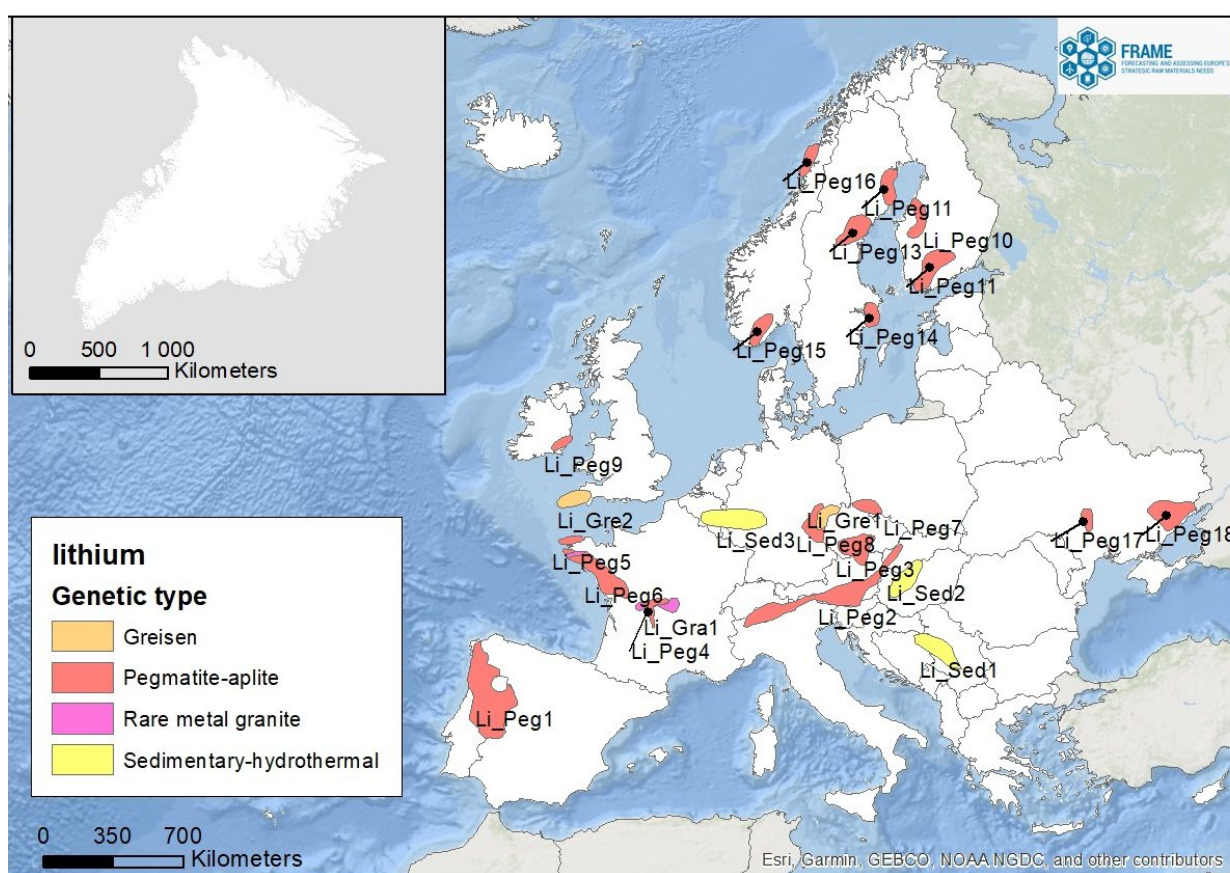


Figure 12 Main metallogenic provinces for lithium in Europe according the genetic type.

Table 6 Keys mineral provinces for lithium ore deposits in Europe.

ID_area	Key mineral province	Main genetic type
Li_Gra1	Rare element belt of French massif central	Rare element granite
Li_Gra2	Audierne bay rare element granite province	Rare element granite
Li_Gre1	Erzgebirge province	Greisen
Li_Gre2	Cornwall province	Greisen
Li_Peg1	Galicia - Centro-Iberian pegmatite province	Pegmatite-aplite
Li_Peg10	Kaustinen pegmatite province	Pegmatite-aplite
Li_Peg11	Somero-Tammela pegmatite province	Pegmatite-aplite
Li_Peg12	Skellefteå pegmatite province	Pegmatite-aplite
Li_Peg13	Västernorrland pegmatite province	Pegmatite-aplite
Li_Peg14	Stockholm pegmatite province	Pegmatite-aplite
Li_Peg15	Setesdal-Bamble-Nissedal pegmatite provinces	Pegmatite-aplite
Li_Peg16	Glomfjord pegmatite province	Pegmatite-aplite
Li_Peg17	Dobra pegmatite province	Pegmatite-aplite
Li_Peg18	Shevchenkivske pegmatite province	Pegmatite-aplite
Li_Peg2	Austroalpine pegmatite province	Pegmatite-aplite
Li_Peg3	Moldanubian pegmatite province	Pegmatite-aplite
Li_Peg4	Ambazac-Creuse-Millevaches province	Pegmatite-aplite
Li_Peg5	Leon pegmatite province	Pegmatite-aplite
Li_Peg6	South Brittany pegmatite province	Pegmatite-aplite
Li_Peg7	Sudetes pegmatite province	Pegmatite-aplite
Li_Peg8	Saxo-Thuringian pegmatite province	Pegmatite-aplite
Li_Peg9	Leinster pegmatite province	Pegmatite-aplite
Li_Sed1	Jadar province	Sedimentary-hydrothermal
Li_Sed2	West Hungary bauxite province	Sedimentary-hydrothermal
Li_Sed3	Ardennes province	Sedimentary-hydrothermal

Key mineral provinces for lithium associated with pegmatites

Numerous Li-rich pegmatites are observed in several pegmatites field, mainly in Finland, Sweden, Ukraine, Portugal, Spain, France, Austria and Ireland but the spodumene-albite type and the spodumene subtype are not the most abundant Li-bearing pegmatites in Europe. They are generally clustered in kilometer-size pegmatite fields (e.g., the **Ambazac** pegmatite field, (Deveaud et al., 2013; Silva et al., 2018), and occur as dikes and/or sills (e.g., **Emmes** pegmatite, Finland, (Eilu, 2012); **Gonçalo** pegmatite field, Portugal, (Ramos, 1998) or lenticular bodies (e.g., Bohemian pegmatites, (Melleton, Gloaguen, Frei, Novák, & Breiter, 2012). Contacts with host-rock range from relatively sharp to progressive, depending on the nature of the host and the depth of emplacement. Host rocks are mainly metasedimentary and/or metavolcanic rocks metamorphosed from lower greenschist to amphibolite facies as well as granite intrusions (e.g., Gonçalo, Ambazac).

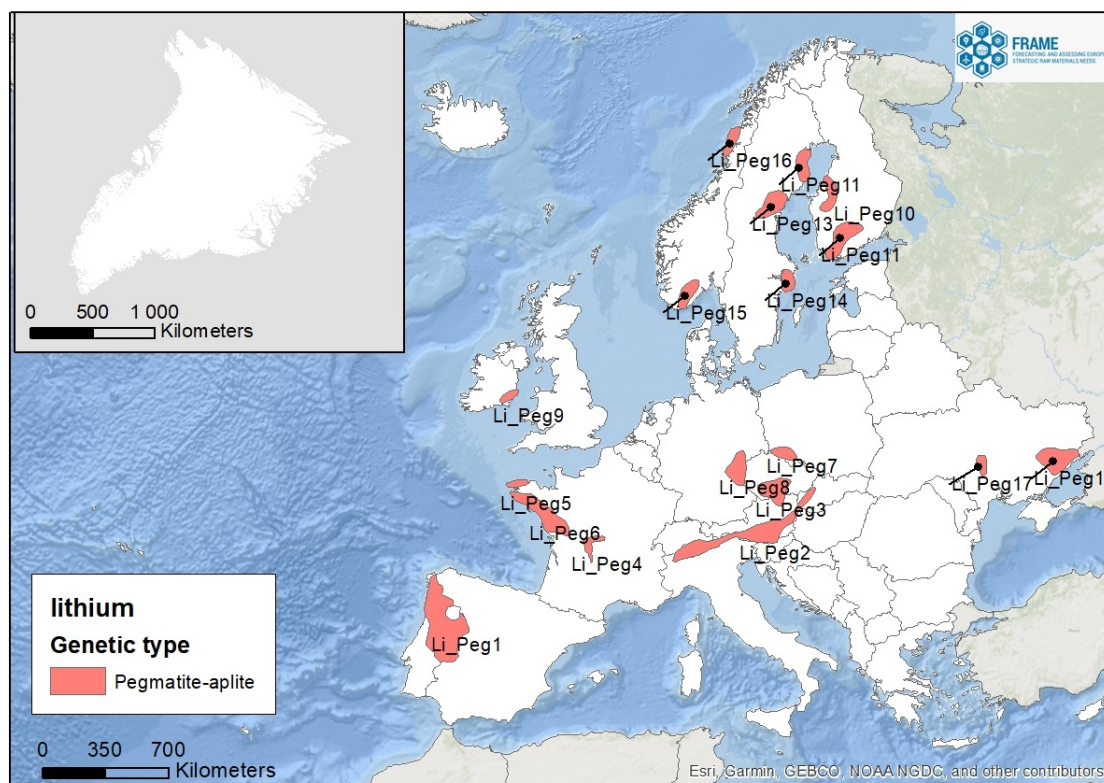


Figure 13 Main metallogenic provinces for lithium-bearing pegmatites-aplites in Europe.

In Ukraine, several field of spodumene and petalite-bearing pegmatites are known in the Archean basement (Pavlunenko, 2010). According to the Geological Survey of Ukraine, the most important is the petalite-pegmatite of the **Polokhivske** deposit, located in the **Shpolyansko-Tashlyktskyi pegmatite province** (Li_Peg17) in the center of Ukraine, which is represented by three steeply-dipping pegmatite bodies (550 m long, 60 m in thickness, grade 1.25% Li_2O). In this province, the resources of the **Nadiya** spodumene-pegmatite are estimated to 728,896t Li_2O . In the east of Ukraine, the **Shevchenkivske pegmatite province** (Li_Peg18) contains several spodumene-bearing pegmatites like the **Shevchenkivskoe** deposit (resources of 69,960 t Li_2O).

In Finland and Sweden, prospective lithium-rich pegmatites are associated with the Svecofennian orogen (1.92-1.77 Ga). Significant lithospheric thickening during the orogeny lead to local migmatisation and formation of S-type granites and pegmatite fields in southern Finland and central Sweden. Lithium mineralization are emplaced in metasedimentary and metavolcanic units along major faults and shear zones between 1820 and 1775 Ma (Alviola, Manttari, Makitie, & Vaasjoki, 2001; Romer & Smeds, 1994, 1997). 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 following: the **Kaustinen pegmatite province** (Li_Peg10) where the Pohjanmaa schist belt hosts the spodumene-bearing **Rapasaari** (reserves of 49,632t Li_2O), **Syväjärvi** (reserves of 20,709 t Li_2O), **Länttä** (reserves of 9,262.20 t Li_2O) and **Outovesi** (reserves of 2,397.60t Li_2O) pegmatite deposits, close to the Vaasa migmatitic complex (Chopin et al., 2020) and references enclosed. In the south of Finland, the **Somero-Tammela pegmatite province** (Li_Peg11) is centered on the Vammala migmatite belt.

Lithium-bearing pegmatites (petalite/spodumene **Luolamaki**, **Hirvikallio** (resources of 2,685 t Li_2O) and **Kietyömaäki** LCT pegmatites) are also located in metasedimentary belts. To the west in central Sweden, the Bothnian basin made of sedimentary and volcanic rocks (1.91-1.86 Ga) host the **Skellefteå** pegmatite province (Li_Peg12) and the **Västernorrland pegmatite province** (Li_Peg13). Pegmatites are found mainly in metasedimentary rocks, frequently associated with anatectic granites (e.g. Härno, Skellefte, Stockholm granites). Petalite-Spodumene pegmatites include **Järkvissle**, **Orrvik** occurrences as well as the 30m-thick Petalite-Amblygonite-Spodumene-bearing **Varuträsk** pegmatite deposit, which is close to the Skellefte shear zone. Numerous pegmatites contain Li-bearing phosphates (amblygonite, triphylite) like **Älggårdsberget** and **Stockberget** pegmatites. In the south of Sweden, the Stockholm pegmatite province (Li_Peg14) host a smallest potential. This province is hosted by the Sörmland basin. According to (Romer & Smeds, 1994) and references enclosed, metasediments and volcanic rocks were strongly deformed, intruded by granitoids and intensively migmatitized during the Svecofennian orogeny. In less metamorphosed zones, numerous intrusions of late orogenic granites and NYF + LCT pegmatites are observed. In the **Utö** archipelago, (type locality of the Li-mineral petalite) several Li-bearing spodumene-petalite pegmatites are well-known.

Another very prospective target is represented by Variscan pegmatites. The European Variscan orogen results of the Late Paleozoic convergence and collision between the Gondwana (south) and the Laurasia-Baltica (north) megacontinent involving several intermediate microcontinents and closures of oceanic domains eg. (Philippe Matte, 1991; P. Matte, 2001). This belt forms a 3000 km long and 700–800 km wide belt that extends from Iberia to Bohemia. The post-orogenic collapse took place around 300 Ma, coeval with extension and development of intramontane coal basins and ca. 315-300 Ma local migmatization (Faure, Mézème, Duguet, Cartier, & Talbot, 2005) These events appear to have been diachronous throughout the Variscan orogeny. According to (Romer & Kroner, 2016), the intense chemical weathering of rocks on the Gondwana continent and the reworking of these weathered clay-bearing products along the Gondwana margin are inferred to be the enriched source from which originate the lithium rich melts generated by the generalized MP-HT migmatitization in the upper Carboniferous time. The well-known **rare-element belt of the north French massif central** eg. (M. Cuney et al., 2002) appears a strong example of this phenomenon. The most important Variscan Lithium-bearing pegmatite province is **the Galica – Centro-Iberian pegmatite province** (Li_Peg1). This province is composed of more than 20 major Li-pegmatite fields review in (Roda-Robles et al., 2018). Most of the intrusion are emplaced in the Neoproterozoic schists through the Central Iberian Zone (CIZ). In the internal thickened Variscan zones (Galicia-Tras-os-Montes zone), intrusions are mainly emplaced in the nappe of the para-autochthonous schists and sometimes up to the nappe of the lower allochton (eg. **Lalín** spodumene-pegmatites, (Fuertes-Fuente, Martin-Izard, Boiron, & Mangas, 2000). The most important pegmatites field for lithium seems to be, in Portugal, the **Barroso-Alvão** (**Barroso** (resources of 241,000 t Li_2O), **Sepeda** (resources of 103,000 t Li_2O), **Adagoi** spodumene pegmatites) and **Gonçalo** pegmatite fields (**Alvarrões** with resources of 51,069t Li_2O) and, at the Spain-Portugal boundary, the **Almendra-Fregeneda** pegmatite field.

In France, the most prospective area for pegmatites is the **Ambazac-Creuse-Millevaches** (Li_Peg4) province, located on the NW of the French massif central. This province encompasses several Lithium-bearing pegmatite fields, some of them including petalite-lepidolite dykes exploited in the XXth century (**Chedeville** pegmatites, (Raimbault, 1998), with an ore production of 7078t between 1929 and 1938). To the west, in the Armorican massif, lithium mineralization is restricted to the thickened Variscan domains (e.g. (Ballèvre, Bosse, Ducassou, & Pitra, 2009), the Léon block in the north-west and the South Armorican domain along the southern coast. The **South Brittany pegmatite province** (Li_Peg6) includes several pegmatites fields over a large surface. Among them, some pegmatites are mineralized in Lithium (Lepidolite subtype, **Saint-Sébastien-sur-Loire**) but the potential remains underexplored. The **Leon pegmatite province** (Li_Peg5) includes numerous pegmatite fields and peraluminous granite intrusion generally rich in tin and boron. Some pegmatites (e.g. **Santec**) contain a lithium enrichment but this province is also strongly under-explored for lithium.

In the Bohemian Massif, which represents the easternmost part of the Variscan belt in Europe, Lithium-bearing pegmatite fields are mainly represented by three provinces, the Sudetes (Li_Peg7) and the **Saxo-Thuringian pegmatite provinces** (Li_Peg8) in the Saxothuringian tectonic zone and the **Moldanubian pegmatite province** (Li_Peg3) in the high-grade metamorphic terranes of the Moldanubian tectonic zone. Lithium-carriers are mainly represented by micas (Lepidolite, Zinnwaldite) and Li-phosphates (Amblygonite-Montebrasite, etc.) and the overall potential for economic lithium-bearing pegmatite deposit seems to be lower compared to the previous area. The Moldanubian area contains mainly LCT pegmatites (e.g.(Ackerman et al., 2017), which appear to be spatially related to migmatitic domes and shear zones. Two distinct periods of pegmatite emplacement appears to be coeval with two metamorphic-anatectic events (Melleton et al., 2012).

In United Kingdom, the main Lithium-rich pegmatite-aplite (review in (Brown et al., 2016) is the **Meldon** aplite located in the **Cornwall province** (Li_Gre2). The **Meldon** aplite is a Li-rich albitic aplite dyke (3.3 km x 25m) with an estimated lithium resource of 45,500.16 t Li₂O. Lithium is mainly hosted by lepidolite but others Li-bearing minerals (petalite, spodumene, amblygonite, elbaite) are also irregularly distributed in the dyke.

In Romania, Spodumene-albite subtype pegmatites are known in the **Conțu-Negovanu** pegmatite field (South Carpathians) where they occurs as ca 500m-long dykes within amphibolite-grade micaschist on the NE side of the Conțu mount(Popescu, Neacșu, Buia, Damian, & Damian, 2013).

In Austria, pegmatites are not Variscan but Lower Permian in age. **Austroalpine pegmatite province** (Li_Peg2) is composed of thousand pegmatites on an extend of 400km, from the north of Torino up to the south of Vienna (Ralf Schuster, Knoll, & Heinrich, 2019). The Austroalpine unit of the Eastern Alps contains important LCT spodumene-bearing pegmatite fields. A good example is represented by the **Weinebene** spodumene-pegmatites (*resources of 109,800 t Li₂O*). These pegmatites appear to be generated by anatexis from mica schists and paragneisses at upper amphibolite to granulite facies (Knoll et al., 2018; Ralf Schuster et al., 2019) coeval with lithospheric extension, causing crustal

basaltic underplating, HT and LP metamorphism, as well as intense magmatic activity (Ralf Schuster & Stüwe, 2008).

Apart from the above-mentioned orogens favorable for mineralization, the others orogens do not appear generally favorable to the presence of mineralization except in certain local areas. This is the case of the Sveconorwegian orogeny (**Glomfjord** and **Setesdal-Bamble-Nissedal pegmatite provinces**). Indeed, despite several thousand of pegmatites, mainly of Niobium-Yttrium-Fluor type (A. Müller et al., 2017), only few contain significant amount of lithium mainly as lepidolite and zinnwaldite. Nevertheless, due to the presence of LCT and mixed NYF-LCT pegmatites and the huge size of the pegmatite fields, the presence of economic lithium pegmatites cannot be ruled out. Globally, the Caledonian orogeny (ca 475-380 Ma) appears poor in Lithium mineralisation at the exception of Ireland. Indeed, the ca. 412 Ma **Leinster LCT pegmatite province** (Barros, Kaeter, Menuge, & Škoda, 2020) and references enclosed) includes pegmatite fields where occur spodumene-rich pegmatites (e.g. **Aclare** with resources of 8,550t Li₂O and **Molyisha** spodumene-albite pegmatites among others).

Key mineral provinces for lithium associated with granites

Lithium-rich high-phosphorus rare element granites are scarce in Europe. In this type of mineralisation, most abundant lithium-carriers are Li-phosphates (amblygonite-montebrazite) and Li-micas (lepidolite and Li-muscovite). Despite their small size (<1 km³) they are the host of large disseminated mineralisation, for example, the **Beauvoir** Li resources are estimated to 375,300t Li₂O (Gloaguen et al., 2018) They are emplaced close to the surface such and show various shapes (Gourcerol et al., 2019) ranging from dyke (**Richemont**, **Tréguennec** in France), tube-like (**Argemela** in Portugal), plug-like (**Beauvoir** in France) or laccolithic (**Montebras** in France). Some amblygonite-quartz veins are sometimes associated with those granites as underline by (Roda-Robles et al., 2018) in Spain, like the **San José – Valdeflorez** deposit (resources of 683,200t Li₂O), composed of Li-bearing hydrothermalized schists crosscutted by a quartz-amblygonite-Montebrazite veins system (Pesquera, Roda-Robles, Gil-Crespo, Valls, & Ruiz, 2020).

In France, the most important target for lithium-rich granites is the **rare element belt** (Michel Cuney et al., 2002) located along the **northern part of the French massif central** (Li_Gra1). This east-west belt includes 4 rare-element granites and rhyolite, for example the well-known **Beauvoir** granite eg. (Cuney, Marignac, & Weisbrod, 1992; Raimbault, Cuney, Azencott, Duthou, & Joron, 1995)) with resources of 375,300t Li₂O, and the **Richemont** rhyolite(Raimbault & Burnol, 1998). To the west, in the Armorican massif, the **Audierne bay rare element granite province** (Li_Gra2) include several dykes of Li-rich high-phosphorus rare element granite with some of them (**Tréguennec-Prat-ar-Hastel** dyke with resources of 66,300 t Li₂O), (Gloaguen et al., 2018) and references enclosed, showing a chemical composition close to the Beauvoir granite.

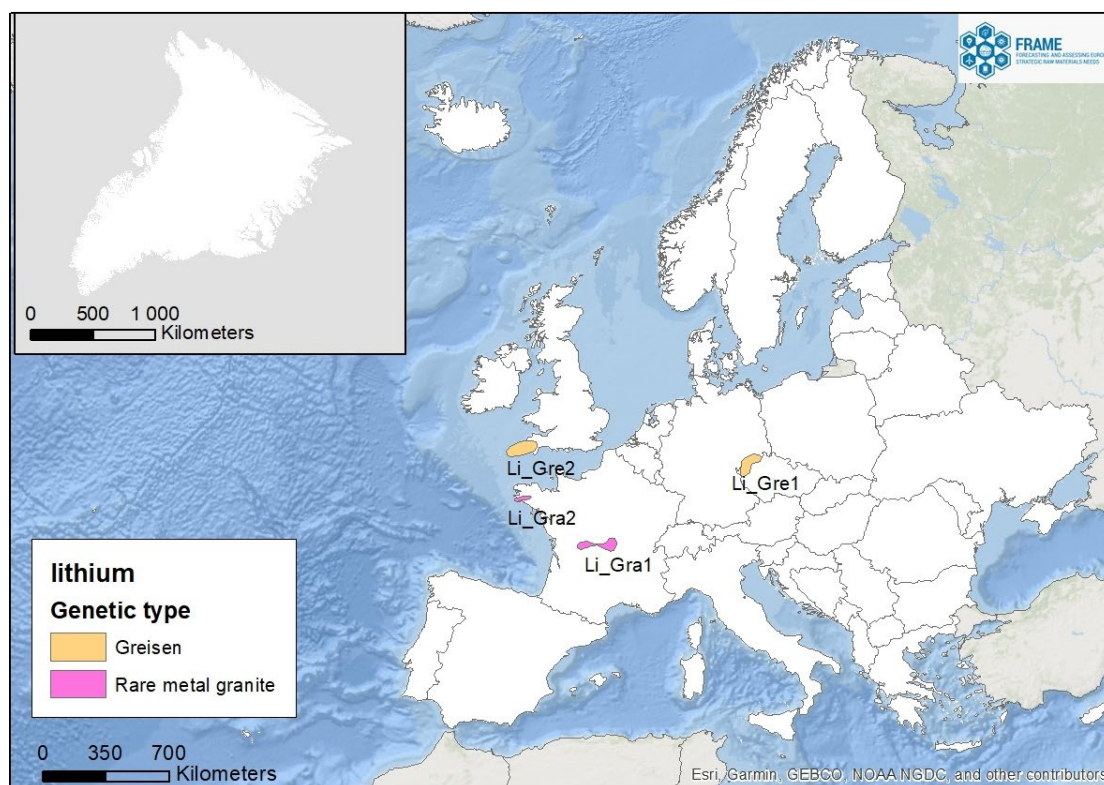


Figure 14 Main metallogenic provinces for lithium-bearing granites and greisens in Europe.

In Iberia (Spain and Portugal) several isolated amblygonite-quartz veins, amblygonite-lepidolite-bearing rare-element granite or Lithium-rich leucogranites are also known in the CIZ (review in (Roda-Robles et al., 2018)) like in the **Argemela** area in Portugal (Charoy & Noronha, 1996; Michaud, Gumiaux, Pichavant, Gloaguen, & Marcoux, 2020) with lithium resources estimated to 49,950 t Li₂O.

In United Kingdom, the **Saint Austell** granite contains a large volume of disseminated Li-bearing micas (Zinnwaldite, Lepidolite) with resources estimated to 2,921,631.77 t Li₂O review in (Brown et al., 2016).

Key mineral provinces for lithium associated with greisens.

Intermediate to low-phosphorus rare element granites have a low lithium content compared to high-phosphorus ones (Černý et al., 2005). Nevertheless, high-temperature hydrothermal alteration could be responsible for the formation of secondary lithium-rich greisens overprinting these rare element granites. These greisens are mainly composed of Li-rich micas (muscovite, lepidolite, zinnwaldite) and quartz, with variable amounts of Li-phosphates (amblygonite-montebrazite series), cassiterite, wolframite, topaz, tourmaline, sericite and chlorite. Conversely, greisens overprinting granite are poor in lithium. According to (Gourcerol et al., 2019) and references enclosed, the Li₂O content in the greisen around the world-class Panasqueira W deposit (Portugal) is only about 732 ppm, whereas Li₂O values from the **Erzgebirge province** vary from 80 to 3100 ppm for greisen of the **Vykmánov** and **Schnöd** rare-element granites. The most important lithium-rich greisens

are located within rare element granites in the **Erzgebirge province** (Li_Gre1) at the Czech-Germany boundary. Numerous greisens are known in this area, the most emblematic being the **Cinovec** greisen with Li resources estimated to 2,921,631t Li₂O and the **Zinnwald** greisen with Li resources estimated to 124,959.69 t Li₂O (Gourcerol et al., 2019). The second region in Czech Republic in the Western Erzgebirge area are Krásnov and Horní Slavkov with 41.199 kt of Li metal.

Secondary deposits, former mining wastes, contain in tailings cca 8.5 kt Li metal.

In United Kingdom, main greisen mineralisation (review in Brown et al., 2016) are located in the **Cornwall province** (Li_Gre2). The **Tregonning-Godolphin** and **Cligga-Head** granites represent small but significant volumes of metasomatised granite with lithium hosted by lepidolite.

Key mineral provinces for lithium associated with sedimentary-hydrothermal mineralisation

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

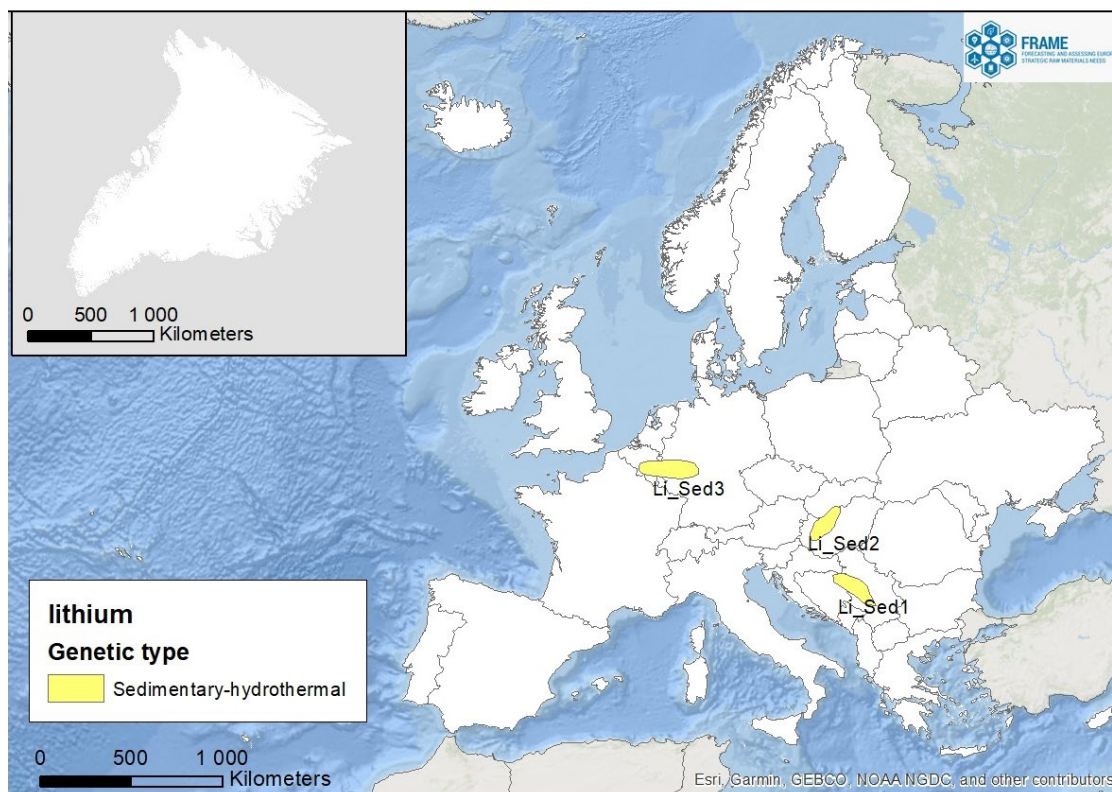


Figure 15: Main metallogenic provinces for sedimentary-hydrothermal lithium mineralization in Europe.

In Serbia, the **Jadar** deposit (resources of 2,524,020t Li₂O) is the most important deposit of the **Jadar province** (Li_Sed1). This deposit is characterized by several 1.5 to 35m-thick lenses of jadarite (Lithium borosilicate, (Stanley et al., 2007) interbedded within a Miocene lacustrine serie close to a basement where granites and spodumene pegmatites occur (Lazić, Kahlenberg, Vulić, Pešić, & Dimitrijević, 2009) suggesting local lithium enrichment in the basement. Nevertheless, the jadarite precipitation process is poorly constrained. Others occurrences in the Miocene lacustrine sediments are mainly Li-bearing montmorillonite.

In Europe, bauxite deposits occur from Spain to Turkey, including parts of southern France, Hungary, Italy, Greece and the Balkans (Bárdossy, 1982). Despite this large number of occurrences, the lithium content of European bauxite remains poorly constrained apart from the **West Hungary bauxite province** (Li_Sed2). Thus, Li-bearing minerals in bauxite deposits are known in Cretaceous bauxites from Hungary (D'Argenio & Mindszenty, 1987) and in Jurassic to Cretaceous bauxites from Greece. The main Li-bearing mineral are lithiophorite and cookeite, disseminated within bauxites (Bárdossy, 1982) In Hungary, these deposits are stratiform where bedrock is a nonuniform karst carbonate rock, in which the bauxite horizons are relatively large (e.g. **Halimba** mining district with bauxite thickness varying from 1 to 40 m).

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 lithiophorite is secondary, related to fluid circulation (Nicholson & Anderton, 1989). Despite the presence of lithiophorite, the amount to lithium is generally low. A first group of deposits in Scotland, Wales (e.g., **Drosgol Mine**), England (**Clews Gill**) (Brown et al., 2016)(in the **Ardennes province** (Li_Sed3) (Belgium: **Ottre, Beez**; Germany: **Harz**) is Cambrian to Early Ordovician in age (Romer, Kirsch, Kroner, & Murphy, 2011; Waldron, Schofield, White, & Barr, 2011). The second group is mainly found in Hungary, where the **Eplény** and **Urkut** Mn deposits are Jurassic in age (Polgári, Philippe, Szábo-Drubina, & Tóth, 2005) These deposits are associated with marine sedimentary rocks mainly composed of bioclastic limestone and black shale. (Romer et al., 2011) suggested that the lithium component derived from chemical weathering of continental crust and was originally concentrated in siliciclastic or carbonate rocks.

Cobalt

Cobalt occurs as relatively common trace to minor constituent in many types deposit types of different commodities. In Europe, the most common deposit types are orthomagmatic Ni-Cu-Co deposits, volcanogenic Cu-Zn-sulfide deposits (VMS), Iron Oxide-Cu-Au deposits (IOCG), 5-element and other vein-type deposits, sediment-hosted Cu deposits, lateritic Ni-Co deposits and metasediment-hosted Cu-Au-Co deposits (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 the 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 these deposits. Currently cobalt is produced only from three mines in Finland in Europe. The Eu consumption of cobalt ores, concentrates and intermediates is ~14 000 t of which 14% comes from within the EU (Finland) and the rest is exported mainly from DRC (European Commission, 2020d).

As a minor constituent, cobalt is often not included in mineral resource and reserve estimates. Where available, data indicate 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 (~290 000 t) and in the lateritic Mokra Gora Ni-Co deposit in Serbia (360 000 t)(Horn et al., 2020)

Based on the clusters of occurrences shown in Figure 5, 34 provinces were delineated. Broadly, the following main cobalt metallogenic zones are:

- 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 Calanides in westernmost Sweden) to Meso-Neoproterozoic to Paleozoic in Norway. All three countries contain a high number of Co-bearing occurrences with Finland having 123, Norway 85 and Sweden 63. In Finland, past production of cobalt came from the Kotalahti and Vammala belts (orthomagmatic Ni-Cu-Co deposits) and from the Outokumpu area Cu-Zn-Ni-Co VMS deposits. Very little Co-production data is available from the Ni-Cu-Co deposits but the Outokumpu area mines (5) produced 75 000 t of Co. Current mine production of Co comes from Kevitsa Ni-Cu-Co-Au-PGE deposit; 450-550 t per year, Kylylahti Cu-Zn-Ni-Co deposit; 450 t per year, and Sotkamo (Talvivaara) Ni-Zn-Cu-Co deposit; estimated to be 500 t per year. In Norway, most significant Co deposits are magmatic Ni-Cu-Co deposits and Co-containing VMS deposits in southern and central Norway (e.g. S-Norway, Løkken, and Sulitjelma areas). Historic Co-production has come from e.g. Ertelien Ni-Cu mine (1789 t) and the Skuterud Cu-Co mine, from southern Norway (Sandstad et al., 2012). In Sweden, most of the known Co-deposits are magmatic Ni-Cu-Co deposits in the Skellefte and Bergslagen areas with historic Co production from Bergslagen area deposits and, e.g. Gladhammar in southern Sweden (Hallberg et al., 2012)

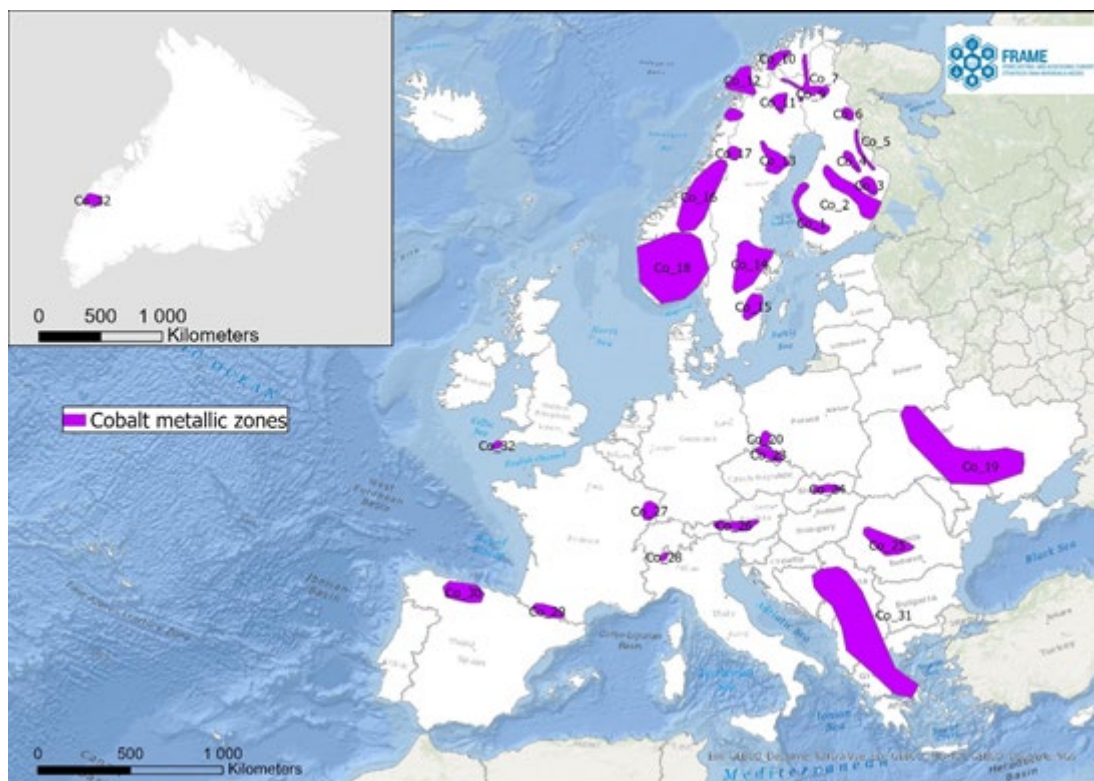


Figure 16 Metalliz zonesprovinces of cobalt in Europe and Greenland.

The bulk of Co-occurrence in **Greenland** are located in western Greenland, in the Archean Maniitsoq Norite belt, which contains some 65 orthomagmatic Ni-Cu-Co±PGE occurrences (North American Nickel, 2015; Stensgaard, Stendal, Kalvig, & Hanghøj, 2017). A small cluster of VMS occurrences is located in southern Greenland associated with Palaeoproterozoic Ketilidian orogen.

The **Balkans 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 occur in Ukraine.

Elsewhere in the Europe, small, mostly historic Co deposits and occurrences can be found related to Variscan and Alpine orogenies, extending from Cantabrian mountains in NW Spain, through Pyrenees and France, northern Italy, Austria, Slovakia and Romania in the east. A cluster of Co-deposits also occur in the SW Poland. They represent a diverse suite of deposit types with sediment-hosted Cu-Co, 5-element vein type, VMS (to SEDEX) deposit and Co-sulfarsenide (vein) type being the most prominent types. In addition, magmatic Ni-Cu-Co deposits occur in Romania and lateritic Ni-Co deposits in SW Poland.

In the British Isles, Co-bearing vein type deposits are clustered in the Cornubian Ore Field in SW England. They are spatially associated with 270-300 Ma aged monzogranite batholiths but represent a later mineralising event to the Sn-Cu stage (Jackson, Willis-Richards, Manning, & Sams, 1989). Some magmatic Ni-Cu-Co occurrences are known from Scotland.

Graphite

The graphite occurrences in Europe, cluster into 30 different provinces (fig. 17 and table 7). Based on the locations of deposit with present or historical production sites, and the amount of information available the most important provinces for graphite in Europe are:

- a) The Fennoscandian shield, 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. In Norway, Sweden and Finland there are more than 50 occurrences registered in each country. The most well known largest deposits is the Skaland graphite deposits on islands of Senja in Norway which have been in production since 1922. In northern Norway historical graphite production has been carried out in three localities, the Skaland area on Senja, the Jennestad area in Vesterålen and in the Hålandsfjord area south of the city of Bodø. Test mining has been taken place at a number of different occurrences. In northern Norway 28 different occurrences have an aggregated, estimated tonnage of 241.6 Mt and average graphite content of 9.3% C.(Gautneb et al., 2020)

In **Finland** about 30 occurrences has been exploited historically and about 20 of these are located within the present borders. The best investigated occurrences are the Piippumäki with 6.4% graphite and Rautalamp and Kämpysuo (12 % graphite) occurrences (Al-Ani, Leinonen, Ahtola, & Salvador, 2020; Palosaari, Latonen, Smått, Raunio, & Eklund, 2020).

In **Sweden** there are 54 known graphite occurrences most of them in the Norrbotten area. There is a mixture of flake and amorphous graphite deposits. The largest and best investigated deposit is the Nunasvarra graphite deposit with 25.6% graphite and 12.3 Mt (E. Lynch, P., Hellström, & Huhma, 2016; E. P. Lynch et al., 2018)

Table 7 Graphite provinces of Europe, grouped based on data input from project partners.

ID_area	area_name	country	Genetic type
Graph1	Rhone	France	Flake
Graph2	Teterivska	Ukraine	Flake
Graph3	Romania	Romania	Flake
Graph4	Drau-Mur	Austria	Amorphous
Graph5	Veitsch	Austria	Amorphous
Graph6	Moldanubikum	Austria	Amorphous
Graph7	Drosendorf	Austria	Amorphous
Graph8	Ukraina2	Ukraine	Flake
Graph9	Porto	Portugal	Unclassified
Graph10	Cabaneros	Spain	Flake

Graph11	Ponteferrada	Spain	Amorphous
Graph12	Sigüenza	Spain	Unknown
Graph13	Boada	Spain	Unknown
Graph14	La Nava	Spain	amorphous
Graph15	Huelva	Spain	Flake
Graph16	Barcelona	Spain	Flake
Graph17	Pyrenees	Spain	Amorphous
Graph18	Västernorrland	Sweden	Unknown
Graph19	Skelleftea	Sweden	Unknown
Graph20	Holandsfjord	Norway	Flake
Graph21	Woxna	Sweden	Flake
Graph22	Central Finland	Finland	flake
Graph23	Piipumaki	Finland	flake
Graph24	Bamble	Norway	flake
Graph25	North Fennoscandia graphite province	Norway/Sweden	flake/amorpous
Graph26	Amitsoq	Greenland	flake
Graph27	Niaqornat	Greenland	flake
Graph28	Kangikajik*	Greenland	flake
Graph29	Kryvyi Rih	Ukraine	flake
Graph30	Thermes	Greece	Amorphous

* contain no occurrences but is drawn based on

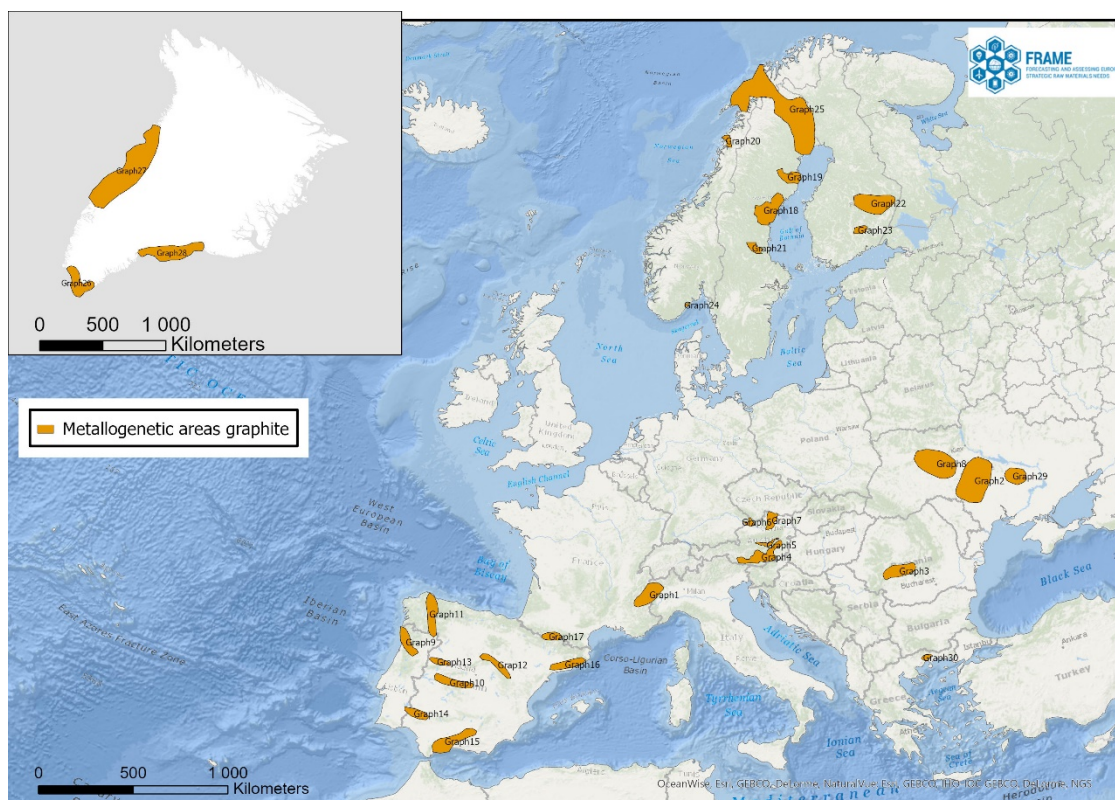


Figure 17 Metallogenetic provinces of graphite in Europe and Greenland.

The graphite occurrences of **Ukraine** are all located on the Ukrainien shield which is broken up by faults into several blocks which comprises Archean to Proterozoic rocks of metasedimentary gneisses, amphibolites and various mafic to acid igneous rocks. The most important graphite occurrence in Ukraine is the Zavalyevskiy deposit, which is also the only in current production. Our database contains 35 occurrences and deposits registered in Ukraine that have aggregated resources of 1615 Mt with an average graphite content of 5.1%.

On **Greenland** there are 7 occurrences in our database, they are described by (Stensgaard et al., 2017). They are all located in Archean or Proterozoic rocks. They are all flake graphite occurrences, and the resources is determined for some of them with tonnages of contained graphite in the range from 1 to 5 Mt and graphite content in the range from 5 to 25%.

In **Spain** there is scattered occurrences all over the Iberian Peninsula, but very few studies are published. In the Aracena mountains in southern Spain graphite occurrences are described from the Neoproterozoic rocks containing meta-sedimentary gneisses, amphibolites and granulites. Graphite occurs stratabound with typical grade of 10 -30% graphite, but can reach up to 50%. A number of mines where in production around 1910 (Rodas et al., 2000). Very little information is publicly available about the other graphite provinces in Spain.

In **Austria** there are 4 provinces with graphite occurrences. In north east the **Dosendorf** graphite province (Graph6 in Fig.17). The graphite occurs in a series of paragneisses, amphibolites and marbles that are of Proterozoic age. Metamorphic conditions have been up to 700-800 °C and 8-11 Kbar (N. Müller et al., 2016). Carbon content of the graphite bearing rocks can be very high up to 60% with a median of 38% (Schedl, Benold, Neinavaie, Lipiarski, & Hobiger, 2016). At about 30 different sites, graphite where mined from 1895 until the last closed in 1994 (Hofbauer, 1995).

The northwestern province the **Moldanubikum (Bavarikum)** (Graph7 on fig.17) graphite province. These occurrences occur in the Kropfmühl- Herzogsdorf complex and comprises graphite schist comparable to the Kropfmühl area in Germany. Graphite content are reported to reach up to 48% (Holzer, 1964). Graphite was produced periodically until 1963.

In the **Veitsch nappe (Kaisersberg)** (Graph5 on fig.17) there are about 50 occurrences which for a large part contain microcrystalline (amorphous) graphite and semi graphite (Rantitsch et al., 2004). Metamorphic conditions have reached upper green schist facies. Carbon content can reach up to 90% locally. In this province the only graphite mine in operation Austria (Kaisersberg) is located producing about 420 t/a of graphite.

In **Drau-Mur (Sothern Styria area)** (Graph4 on fig. 17) the area is dived into two different tectonic units. Host rocks are believed to be of Paleozoic ages and are metamorphosed up to 500-600°C and 6-10 Kbar. Graphite occurs in several layers reaching thicknesses up to about 1 meter. Graphite has been mined periodically in this area at a couple of deposits, the last mining activity was in 1916 (R. Schuster, Pestal, & Reitner, 2006; Ucik, 1992)

In **Germany** in the **Kropfmühl** area in the Passau forest and southwards towards the Danube river (Weinelt, 1987) describes that in 1846 graphite was found in 33 different places. Graphite in this area is known since Roman time and active mining started around 1550. The geology of the Kropfmühl mine is described by (Krüger, Lehrberger, Hoffmann, & Reiser, 2017).

The most important graphite occurrences in **Romania** are known in the central part of the South Carpathians (Parâng and Căpățânei Mts.) in the Danubian Domain. Exploitation started in 1939-1942 and all mines were closed in 1994. Graphite occurs as discontinuous strata, lenses, nests hosted in graphite-carbonate schist, paragneiss and marble overprinted by migmatisations, injected by concordant and discordant porphyric and/or hypidiomorphic granites. The ore is folded and faulted with large variations of carbon concentrations. Twenty two significant graphite occurrences are known, with a total estimated reserve of 166 Mt (1964-1967) and an average content of 10-45 % C.

Future potential and discussions

The purpose of this deliverable is to organize and present data on the occurrences of lithium, cobalt and graphite in Europe with emphasis on the prospectivity and potential areas. The maps show that there are number of ore deposits, occurrences and favorable areas where geological processes have enriched lithium, cobalt and graphite. It is beyond the scope of the FRAME project and WP5 to investigate in detail individual deposits or occurrences that would be directly applicable for mining companies and investors. Our maps and databases are however useful for political overview and planning of future detailed research.

Lithium: Up to date, battery grade lithium is only produced from the processing of so-called “conventional resources”: spodumene-bearing ores and lithium-rich brines. In Europe, significant spodumene-bearing pegmatites are mainly located in Portugal, Finland, Sweden, Austria, Ireland and Spain that need to be developed. Nevertheless, most of the hard-rock lithium resources in Europe are “unconventional” lithium resources mainly under the form of micas (Zinnwaldite, lepidolite, Li-muscovite), alumino-silicate (petalite), phosphates (amblygonite-montebrazite) or jadarite. To unlock the European potential a strong R&D input in the field of mineral processing is required to remove the technological barrier that ore processing represents on the mineral potential. Note that each ore and each Li-mineral carrier require a specific mineral processing to extract lithium. This is mandatory to produce economically Li battery-grade lithium from non-conventional deposits that represent the most important part of the European lithium potential otherwise the EU will remain under the threat of CO₂-intensive foreign supply.

Cobalt: Historical production of cobalt has taken place in many European countries. This has, in many cases, been small-scale production of cobalt as a by-product of other metals. Currently, cobalt is only produced in Finland and in Norway (in Norway based on imported Nickel matte). However, as evident in the maps and databases, many of the historical mining regions still have potential for future production from existing resources and from new discoveries as evidenced by renewed interest in certain areas, e.g. Slovakia, NW Spain, N Italy and Austria. Compared to Li and graphite, Co grades vary greatly between deposit types and even within deposit types, such as VMS deposits. Typical cobalt grades are in the 0.01 to 0.05 % range, in some cases 0.1-0.2 % and rarely reaching %-concentration in some vein type deposits, requiring relatively high Co prices to make it interesting from a purely economic stand-point. Cobalt extraction is further complicated by the fact that it rarely occurs as its own minerals, and a significant portion of contained Co in any deposit can be hosted in a mineral phase that is rejected from the main commodity concentrate, such as common Fe-sulphide minerals, especially pyrite. Efficient extraction of available cobalt resources requires advancement of existing extraction technologies and developing new methods.

Graphite: Graphite is a commodity that Europe has produced since Roman times. Graphite is a mineral that commonly occurs in metasedimentary rocks of metamorphic grade above upper greenschist facies, that is in geological terranes that mainly occur in the Nordic countries and in Ukraine, on several areas on Greenland and these are where the largest

potential is expected. In middle and southern Europe graphite occurs in a several minor deposits that have been producers in the past. A number of deposits have recently been identified in the Nordic countries with qualities documented to fulfil the requirements for batteries and graphene. We believe that the areas outlined here as favorable for graphite are the areas where, exploration should be targeted to find new potential occurrences.



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Appendix 1 Comparison of M4EU/Inspire codelist and codelist use in this report for genetic types of ore deposits.

Below is a table that shows the INSPIRE code list “DepositTypeType “ and the the code list for genetic types of ore deposits. In green and yellow are those of our codes that have corresponding inspire code (but on the same line) those code with grey color in the rightern column do not have a corresponding code in the leftern inspire code list.

Table 8 Appendix table; The deficiency of INSPIRE codes compared to codes for genetic types used in WP5.

Common_Terminology_Minerals4EU-V1.0.docx	WP 5 code list
DepositTypeType	Depost type
bauxite	5-element vein type
calcrete	Black schist
gossan	Brines
laterite	Graphite (amorph)
residualOrSurficial phosphorite	Graphite (flake)
anthropogenic deposit	Graphite (unclassified)
eluvial placer	Greisen
alluvial placer	IOCG
shoreline / marine placer	Laterite
eolian placer	Magmatic Fe-Ti-V
paleoplacer	Magmatic hydrothermal
banded iron formation (BIF)	Magmatic Ni-Cu-Co
oolitic iron / ironstone	Metamorphic
sedimentary manganese	Orogenic Au
sedimentary phosphorite	Pegmatite-aplite
stratiform barite	Rare metal granite
evaporite	Sediment hosted Cu-Co
carbonate-hosted	Sedimentary-hydrothermal
sandstone-hosted	Sulfarsenides
shale-hosted (incl. SEDEX)	Unclassified
layered complex	Vein type
mafic to ultramafic effusive volcanism	VMS deposit
mafic to ultramafic intrusion	
komatiite	
anorthosite	
ophiolite	
granitic igneous rocks and pegmatites	
greisen	
porphyry	
iron oxide copper gold (IOCG)	
iron oxide apatite (IOA)	
skarn and carbonate replacement	

hornfels	
polymetallic manto	
Carlin-type carbonate-hosted Au-Ag	
kimberlite and lamproite	
carbonatite	
unsaturated and saturated syenitic and alkali granitic igneous rocks and pegmatites	
low-sulphidation	
high-sulphidation	
mafic volcanism Cu–Zn massive sulphide deposits	
bimodal and felsic volcanism Cu-Pb-Zn VMS and transitional magmatic deposits	
vein, including polymetallic and 5 element vein (Bi, Co, Ni, Ag, U)	
orogenic gold	
aggregate	
dimension stone	
organic	
non-organic (incl. U)	
meteorite impact	

Only 9 of 23 different genetic types of Li, Co and Graphite deposits have an INSPIRE equivalent code list value used. Those that have a matching code value in eh INSPIRE list is marked with a green color. Those that are not marked with green color in right column do not have an equivalent Inspire code.

The deficient INSPIRE codelist prevent a proper integration of wp5 data with INSPIRE, this is outside the control of FRAME and wp5 per date.