



# FRAME

FORECASTING AND ASSESSING EUROPE'S  
STRATEGIC RAW MATERIALS NEEDS

## DELIVERABLE D5.3

Energy critical elements and minerals in Europe; occurrence, types, characteristics, formation, and future potential for European production (Part 1 report).



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## DELIVERABLE D5.3

Energy critical elements and minerals in Europe; occurrence, types, characteristics, formation, and future potential for European production (Part 1 report).

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## Executive summary

### Goal:

To present a report which gives an overview of the production and potential of lithium cobalt and graphite in Europe. Describe the geological processes that resulted in the formation and enrichment of the energy critical materials and present this information in reports, maps, and databases, all downloadable from the web.

### Methods:

The project partners and the Eurogeosurveys MREG members supplied the project with data from national databases. The project aggregated, simplified, and harmonised this information. In addition, data from several academic studies were also collected. The data collection took place over nearly two years. During this period, preliminary maps were presented. A simple data table was the basis for maps created in ArcGIS. These maps were then organised and put on the EGD web servers. The raw data is presented in Part 2 of this report. Lithium, cobalt and graphite are very different commodities and have very little in common from a geological perspective. Identifying common criteria for selecting localities was, therefore, not possible. When lithium and graphite localities could be regarded as enriched, they were included. For cobalt, we considered every locality (ore deposits) with > 100 ppm cobalt as an enrichment. For some countries, this limit was set higher to include a higher proportion of significant localities.

### Results:

Our final maps show the distribution in Europe of:

- 598 lithium occurrences
- 530 cobalt occurrences
- 521 graphite occurrences

We identified every geological setting where lithium occurrences are formed in Europe. These include 1) Pegmatite-aplite; 2) Rare-element granite; 3) Greisen; 4) Sedimentary Hydrothermal (including one brine occurrence in Poland). The Jadar type lithium occurrence probably represents the largest lithium resource in Europe. Lastly, some lithium occurrences are of an unknown type. The lithium occurrences are distributed across 18 different metallogenic provinces.

Cobalt naturally occurs as a trace to a minor constituent in many different ore deposit types and can be a significant by-product in some deposit types. The most important cobalt occurrence type is magmatic Ni-Cu-Co. Another important cobalt occurrence-type is associated with hydrothermal processes, where metals are transported by saline water-based fluids. This process generates a wide variety of different ore deposits in a variety of geological settings in which the volcanic massive sulphide deposits (VMS) are the most important. Lastly, are the cobalt occurrences where



weathering processes on mafic and especially ultramafic Mg-rich rock formations have formed lateritic Ni-Co deposits. These are formed by surface waters transporting and depositing metals (Fe, Ni, Co) downwards during the weathering process. This latter type is particularly common in the Balkan peninsula. The different cobalt occurrences are located in 31 different metallogenetic zones.

The graphite occurrences in Europe represent almost entirely metamorphic organic matter. The greatest potential is found in the Precambrian shield areas in Scandinavia and Ukraine. In these areas, several hundreds of million tons of resources have been identified.

### **Recommendations:**

This study has shown that lithium, cobalt and graphite are not rare in Europe. If the European Union wants to reduce the criticality of these important raw materials, geological resources are available. Our ability to extract these raw materials will depend on our acceptance of mining. For lithium and cobalt, there are occurrences where these elements are naturally associated as companion components and these occurrences cluster in several metallic provinces. It is crucial to improve the knowledge on the true potential of lithium cobalt and graphite in Europe. Industry can then target the right prospects once conditions - the combination of economic, environmental, and social factors – are favourable.



## 1. Introduction

With the Paris agreement (UNFCCC, 2015), the UN member states have directly and indirectly decided on a change in how we produce, store and use energy. This decision will lead to a change and increase in raw material demand that will hit Europe and the rest of the world like a tsunami if the goals of the Paris agreement are to be met. A scenario with a threefold increase in demand for materials such as lithium, cobalt and graphite is natural and unavoidable (Bobba et al., 2020). The European Commission have defined lithium, cobalt and graphite together with more than 25 other elements as critical (European Commission, 2020b). Reducing criticality could be achieved if Europe can ensure that more critical raw materials are produced from European sources. Europe needs an overview and should investigate every locality where geological processes have resulted in an enrichment of the critical elements. This is the essence of the FRAME Project and Work Package 5's focus on lithium, cobalt and graphite. This report is in two parts. The current report represents Part 1, and the data list of our raw data is found in Part 2.

The main aim of this deliverable is to finalize Work Package 5 (WP5). Since the start, WP5 has delivered its products and data for multi-purpose use, and participants have contributed to other works packages, data compilation and publications, e.g., (Bertrand et al., 2020; de Oliveira et al., 2020; Gautneb et al., 2020a; Sadeghi et al., 2020a; Sadeghi et al., 2020b). WP5 also delivered its maps as part of the EU commission's booth at the PDAC conference and trade show in 2019 and 2020.

The target readers for this report are those with limited knowledge of geology, such as planners and decision-makers in the European Commission and officials at the national level. Thus, we have tried to make this contribution as concise as possible. Geological details and country-specific information that naturally are found elsewhere are only included where we find it appropriate.

Some sections of this report partly repeat what we have previously delivered. **The repetition intends to provide readers with the essentials of WP5 in one document.**

The FRAME project and WP5 are not alone in having an interest in the energy critical elements. For instance, the European Commission published its 4<sup>th</sup> report on criticality in 2020 (Bobba et al., 2020; European Commission, 2020b; Latunussa et al., 2020), and several academic studies have been performed on this topic during the project period, e.g. (Gourcerol et al., 2019; Horn et al., 2021). The European Battery Alliance established in 2017 ([www.eba250.com](http://www.eba250.com)) has among its 18 tasks the following:

"Facilitate the expansion/creation of European sources of raw materials."

The FRAME project and the WP5 main aim is to provide easy access to ground deposit data for such a task.



In the field of mineral resources, there are probably no sets of materials that are more diverse than lithium, cobalt and graphite. However, what these elements and minerals have in common is that they are used to manufacture rechargeable batteries. On the other hand, across the fields of geology, production and marketing, there are some similarities. For example, cobalt is always an "accompanying element" and is sold on the international markets as concentrates and intermediate products (e.g., Cobalt-hydroxide), refined to its component metals often far from the primary mining source. In contrast, graphite is always produced as a finished product near the mine and sold to individual customers following tailor-made specifications. Most of the value chain includes private companies. Lithium has an intermediate position, so lithium-bearing minerals can be sold directly (as ceramic and glass flux) or processed in chemical factories to produce the desired end product. This diversity of levels of processing affects the way we present this complex matter and is reflected in varied formats of the subchapters dedicated to the topics of lithium, cobalt and graphite.

## 2. Materials, methods and definitions

### 2.1 Data collection, an overview of raw data

From the partners listed in Chapter 2, WP 5 received information on lithium, cobalt, and graphite occurrences registered in the national databases. The FRAME dataset contains localities representing everything from active mines, abandoned mines, including old artisanal type productions sites and small showings. All represent localities where the geology has favoured enrichment above typical values for lithium cobalt and graphite. For cobalt occurrences, in cases where average cobalt content is known, we set a cut-off level of 100 ppm Co, meaning that occurrences registered with, for instance, copper as the main commodity can be listed as a copper occurrence in The FRAME dataset. For some countries, this cut-off level was set higher.

Table 1 gives the distribution of the occurrences by country.

*Table 1. The number of occurrences in every contributing country.*

| Country/commodity             | N   | Country/commodity      | N   |
|-------------------------------|-----|------------------------|-----|
| <b>Albania</b>                | 9   | <b>North Macedonia</b> | 5   |
| Co                            | 9   | Co                     | 4   |
| <b>Austria</b>                | 298 | Li                     | 1   |
| Co                            | 16  | <b>Norway</b>          | 159 |
| Graphite                      | 232 | Co                     | 85  |
| Li                            | 50  | Graphite               | 59  |
| <b>Belgium</b>                | 8   | Li                     | 15  |
| Li                            | 8   | <b>Poland</b>          | 43  |
| <b>Bosnia and Herzegovina</b> | 3   | Co                     | 32  |
| Co                            | 2   | Li                     | 11  |
| Li                            | 1   | <b>Portugal</b>        | 209 |
| <b>Czech Republic</b>         | 67  | Graphite               | 4   |
| Co                            | 4   | Li                     | 205 |

|                  |     |                       |      |
|------------------|-----|-----------------------|------|
| Graphite         | 31  | <b>Romania</b>        | 28   |
| Li               | 32  | Co                    | 13   |
| <b>Finland</b>   | 166 | <b>Graphite</b>       | 10   |
| Co               | 123 | Li                    | 5    |
| Graphite         | 11  | <b>Serbia</b>         | 13   |
| Li               | 32  | Co                    | 5    |
| <b>France</b>    | 76  | Li                    | 8    |
| Co               | 18  | <b>Slovakia</b>       | 13   |
| Graphite         | 15  | Co                    | 6    |
| Li               | 43  | Graphite              | 1    |
| <b>Germany</b>   | 21  | Li                    | 6    |
| Graphite         | 1   | <b>Slovenia</b>       | 3    |
| Li               | 20  | Graphite              | 2    |
| <b>Greece</b>    | 11  | Li                    | 1    |
| Co               | 5   | <b>Spain</b>          | 131  |
| Graphite         | 2   | Co                    | 34   |
| Li               | 4   | Graphite              | 30   |
| <b>Greenland</b> | 83  | Li                    | 67   |
| Co               | 70  | <b>Sweden</b>         | 166  |
| Graphite         | 10  | Co                    | 63   |
| Li               | 3   | Graphite              | 75   |
| <b>Hungary</b>   | 8   | Li                    | 28   |
| Li               | 8   | <b>Switzerland</b>    | 2    |
| <b>Ireland</b>   | 11  | Li                    | 2    |
| Co               | 1   | <b>Ukraine</b>        | 64   |
| Li               | 10  | Co                    | 16   |
| <b>Italy</b>     | 21  | Graphite              | 35   |
| Co               | 4   | Li                    | 13   |
| Graphite         | 3   | <b>United Kingdom</b> | 29   |
| Li               | 14  | Co                    | 18   |
| <b>Kosovo</b>    | 2   | Li                    | 11   |
| Co               | 2   | <b>Grand Total</b>    | 1649 |

Interactive maps accessible on the web can be found here: [EGDI \(geus.dk\)](https://geus.dk/EGDI).

## 2.2 Definitions

When describing the localities listed in 3.1 and part 2 of this report of lithium, cobalt and graphite, we describe the localities using widely varying levels of existing data. These occurrences can range from world-class deposits currently in production by publicly listed companies to small historical showings with little existing information. We use terminology that is not self-explanatory and could be unfamiliar to those with no background in economic geology. We provide some definitions below. We use the term *occurrence* when we describe generic locality for lithium, cobalt and graphite without any other precision.



### 2.2.1 Occurrence type

INSPIRE uses the term occurrence type (OccurrenceTypeType), from which we have adopted the following vocabulary:

**Occurrence:** An occurrence is a locality with an enrichment above the normal (background) value. There is no measure of economic value or probability of mining with profit. Therefore, our definition may vary from what some other writers use, where an occurrence is a locality with little probability of economic extraction (Goodenough et al., 2016). In our work, every locality is identified as a place where geological processes have resulted in a mineralogical enrichment.

**Deposit:** A deposit is a locality with an enrichment, that in addition, has an estimation of grade and tonnage. This estimation can be compliant with international standards or noncompliant. We do not infer any economic significance since this will vary with many time variable factors.

**Prospect:** A prospect is defined according to INSPIRE as an area that is a potential site of mineral deposits, based on preliminary exploration or previous exploration. A prospect usually includes one or more occurrences. Grade and/or tonnage information may or may not be available.

**Commodity type:** For commodity types, we have used the INSPIRE-defined types; Li, Co, and graphite. Additional precision should be unnecessary.

### 2.2.2 Status

The FRAME dataset contains information on the status of the mines and occurrences. However, this information is probably not accurate. Several occurrences are found in conflict areas of Europe where, at the time of writing, there exists military or political instability. Such situations influence mining production. In addition, many mines, particularly those producing industrial minerals (in our case, lithium and graphite), are privately owned, and activity information is not available. INSPIRE uses the term mine status (MineStatusType), for which we have used the following vocabulary:

**Active:** This is a mine with current production; however, because our data might be a little out of date for some countries so this term may also include a) mines that have become periodically active recently, b) recently put under care and maintenance or c) recently closed. For cobalt and laterite, there are some deposits where a cobalt potential is identified but no production currently. These special cases are listed as "active (no Co production)"

Lithium and cobalt are commodities that almost always occur as a by-product or accompanying element associated with the main product. The lithium production from a pegmatite might be very small compared to the rest of the production and only periodically. For cobalt, the actual production usually happens at the refinery stage, possibly far from the mine and sometimes in other countries. If an active mine reports cobalt, even if it is a small fraction of its total production, it will be regarded as active for cobalt.

**Closed:** Most commonly, this term is used for historic mines where the activity has been abandoned for some time. However, there is currently no definition of how small the production has to be before the production permanently stops and for the mine to be classified as closed. Metal mining in Europe has been taken place since the Bronze age. Our definition of the term "closed" might therefore include very old mining activity.

**Not exploited:** This term is usually used for localities where a resource is located or inferred, usually based on exploration findings. The level of information can be somewhat variable and can include everything from a sample showing an enrichment above normal values or a deposit with a full bankable feasibility study seeking investors before production can start.

### 2.2.3 Commodity type

Here we have used the INSPIRE defined types: Li, Co, and graphite. Additional precision should be unnecessary.

### 2.2.4 Deposit Types

INSPIRE uses the definition *DepositTypeType*, which we have tailored for our purposes. They are defined and described in detail in D5.2. A different data variable name is listed in and used in the descriptions in chapter 3.

## 3. Occurrences of Lithium, Cobalt and Graphite

In this chapter, we provide an overview of the occurrences of lithium, cobalt and graphite in Europe. Each subchapter is divided into sections that review different geological processes (deposit types) that have formed the occurrences and a section that describes the provinces where the occurrences occur and are clustered.

### 3.1 Lithium

#### 3.1.1 Geological processes

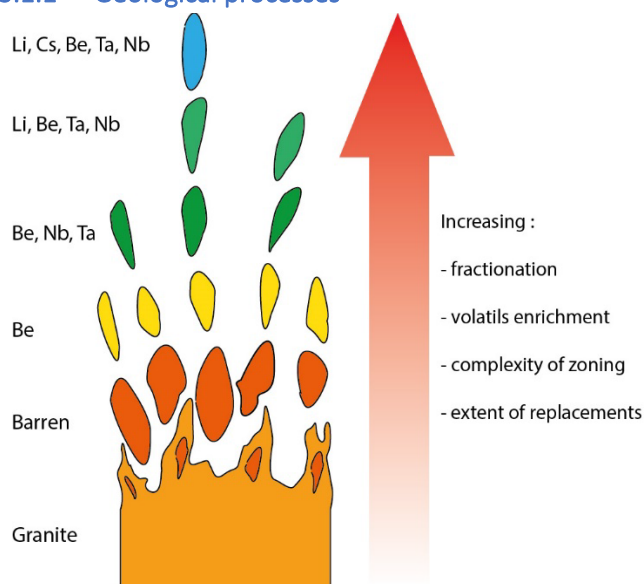


Figure 1. Chemical evolution through a lithium-rich pegmatite group with distance volatiles enrichment. Modified from (London, 2008)

Lithium is mainly concentrated by two main processes (Černý et al., 2005): 1) **at depth by the fractional crystallisation of granite intrusion** (Figure 1) and/or **by the partial melting of Li-rich paleo-sediments** (Figure. 2) and 2) **at earth surface by evaporation of Li-bearing fluids** (Figure 3) that result from host Li-bearing rock weathering, for example in a salar or from rock alteration in geothermal context, for example in a volcanic caldera.

Lithium related to magmatic processes corresponds to hard-

rock ores, typically spodumene-bearing pegmatites and rare-metal granites (Figure 4). The magmatic process responsible for the lithium enrichment is the following: After the emplacement of felsic intrusion and during its cooling, the crystallisation of anhydrous minerals such as potassium feldspar (~40% vol.), quartz (~30% vol.), and plagioclase (~20% vol.) led to an increase of the relative concentration of incompatible elements (water, lithium, phosphorus, etc.) in residual magma. This increase is due to anhydrous rock-forming minerals (representing around 90% of the rock) that poorly integrate lithium within their structure. Successive fractional crystallisation phenomena within granodioritic to granite intrusive complexes should generate residual magmas enriched in dissolved water and volatile elements (Černý et al., 2005). An alternative hypothesis is the partial melting of Li-rich sediments, e.g. (Gourcerol et al., 2019), for example, Li-rich meta-evaporites, that may form Li-bearing pegmatites and/or rare-metal granites above melted areas.

Figure 2. Anatectic model for the generation of pegmatites (barren and Li-rich) and rare-metal granites. Some European mineralisation are given. Modified from (Gourcerol et al., 2019).

Due to the similar ionic radius between  $\text{Li}^+$  (76 pm) and  $\text{Mg}^{2+}$  (72 pm), lithium, in six-fold coordination in the phyllosilicates (Wenger and Armbruster, 1991), replaces magnesium in the octahedral sites as well as in the interfoliar position to balance charges in clays. Consequently, lithium is mainly carried by clays on the earth's surface, produced particularly by supergene weathering. The partitioning of lithium between fluids and rocks during fluid-rock interaction depends on several parameters. The main parameters are the fluid-rock interaction temperature, the type of fluids (salt content, pH, etc.), the lithium content of the host rocks, the mineralogical carriers of lithium and the structural position of lithium (exchangeable versus not exchangeable), particle size and porosity-permeability (Romer et al., 2014). From these parameters, the fluid-rock interaction temperature is one of the most important factors. During weathering of lithium-bearing rocks by fluids, there is a competition between the dissolution rate of primary minerals and the formation rate of secondary minerals (Pogge von Strandmann et al., 2020). If

the primary minerals are dissolved without forming the secondary minerals, mainly clays, the lithium content of the fluids will be significant.

Conversely, if there is a significant formation of secondary minerals, these minerals sequester a large part of the lithium. Arid semi-closed basins are favourable traps for lithium (e.g. salar and/or lithium-bearing clay layers, Figure 3 and Figure 4) if lithium is available from neighbouring rocks that form the basement. Indeed, Li-bearing waters are trapped in the basins, and the lithium is concentrated by evaporation and by water rocks alteration at the bottom of the basin (Houston et al., 2011). Another favourable context is represented by volcanic caldera under arid climate. Lithium is leached from Li-rich volcanic rocks (e.g., rhyolite) by hot fluids circulation and embedded in lacustrine clay levels in the caldera. The arid climate prevents the dilution of the water lithium content (Castor and Henry, 2020).

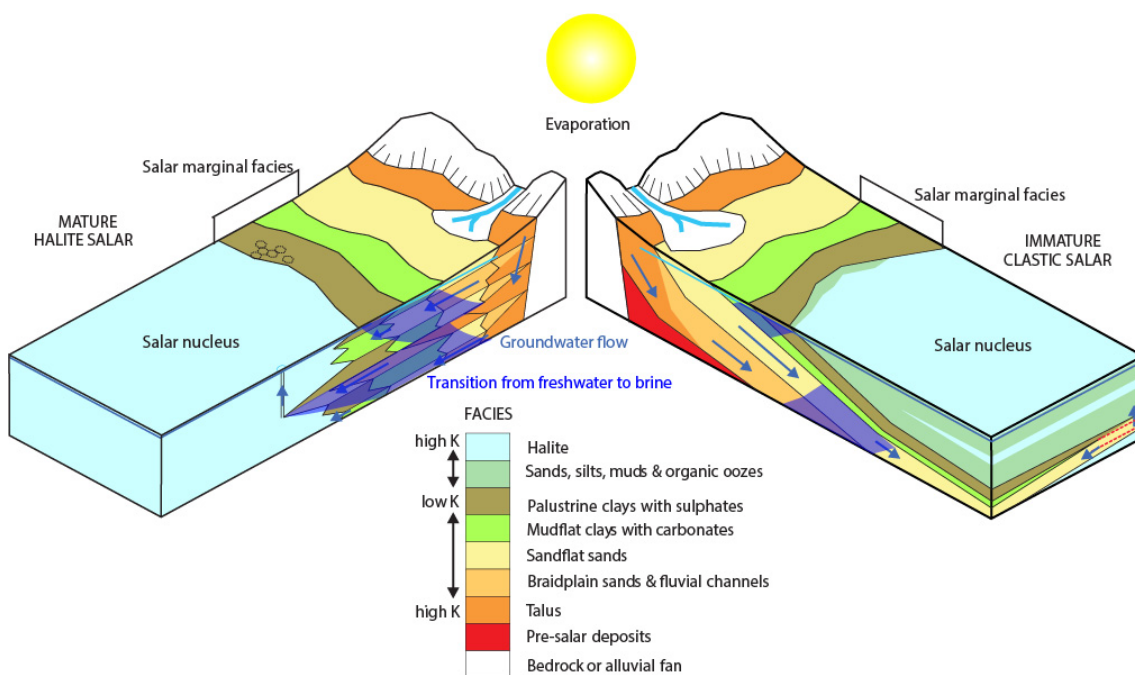


Figure 3. Block models of mature and immature salars showing the distribution of facies and main hydrological components. In the mature model, extension and recession of the marginal facies as a result of tectonism and climate variation lead to the possibility of dilute waters being transferred into the nucleus. In the immature model, while the marginal conditions have been simplified for clarity, the transmission of dilute waters into the nucleus is also possible. K refers to the hydraulic conductivity of the different units. Modified from (Houston et al., 2011)

### 3.1.2 Deposit types

High-purity lithium can be produced from **two distinct deposit types** that are identified and defined as **conventional lithium deposits** (Table 1). They are:

- 1) **brine deposits** hosted by salars, e.g. (Christmann et al., 2015) (Munk et al., 2016), where lithium is in ionic form, dissolved in brines at a grade of about 0.1%  $\text{Li}_2\text{O}$ ; **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.** Nevertheless, several geothermal brines, rich in lithium, are recognized in Europe (e.g., Upper Rhine valley, Italy, Cornwall)
- 2) **hard-rock deposits** where lithium is hosted by various Li-bearing minerals (Christmann et al., 2015; Gourcerol et al., 2019; Kesler et al., 2012), with a lithium grade

that generally varies from ca 0.6 to ca 1.0% Li<sub>2</sub>O. 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.

The second group of deposits is named **unconventional Li-deposit types** (Table1). This group encompasses a wide range of lithium mineralisation, from various hard-rock 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. This group is 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), frequently including an important role played by the arid climate to form Li-bearing evaporates and/or supergene enrichments. Geothermal and oilfield brines localised in such environments are frequently rich in lithium.

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



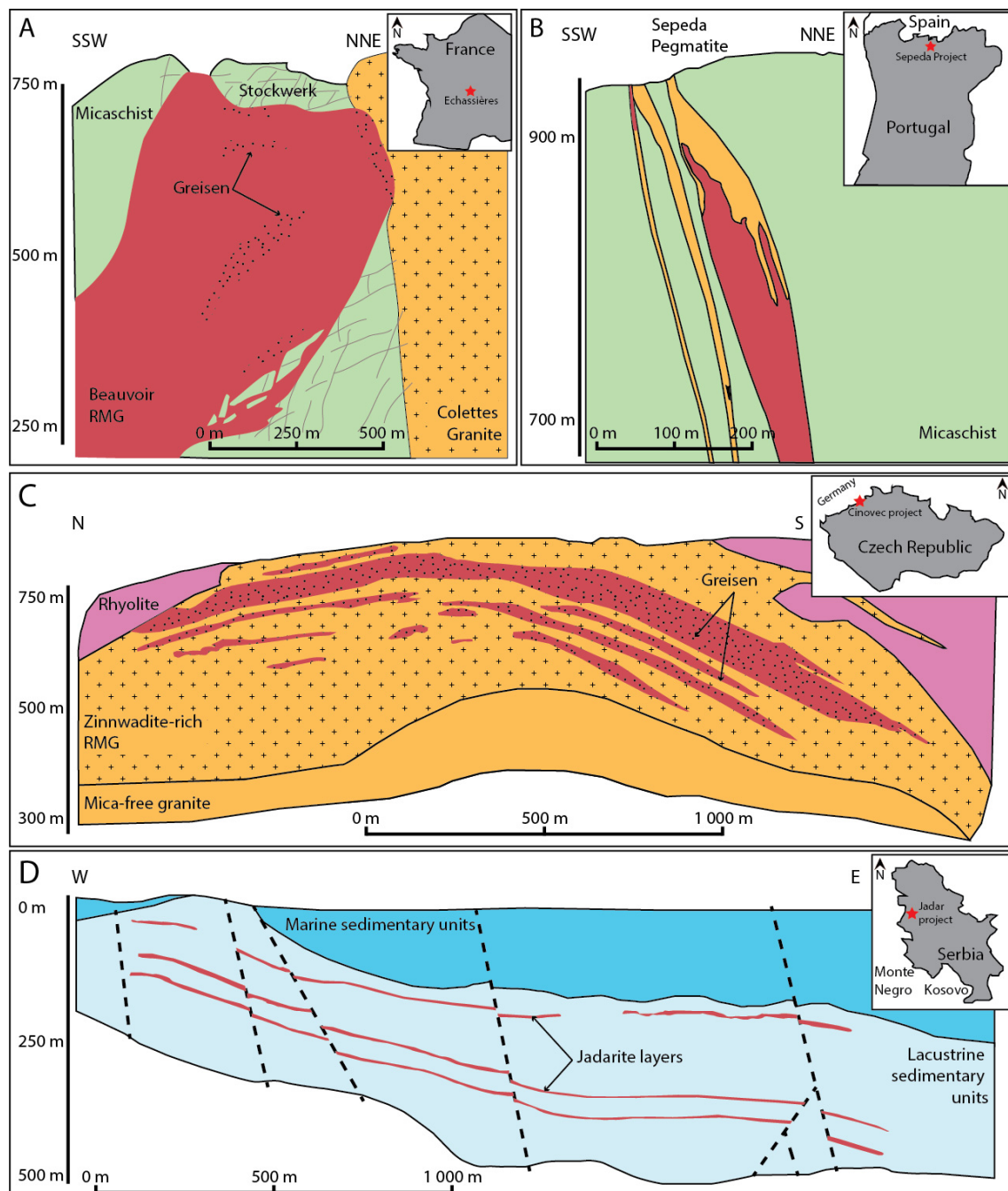


Figure 4. Cross sections of various lithium deposits. Lithium-bearing units are identified in red in each section. A) Beauvoir RMG (France) and related stockwork; B) Sepeda pegmatite in Portugal; orange area represents barren pegmatite. C) Cínovec deposit in the Czech Republic; D) Jadar Basin in Serbia and location of the jadarite layers; modified from Gourcerol et al. (2019) and references enclosed.

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

| Conventional ore deposit | Type | Magmatic                     | Magmatic-hydrothermal | Sedimentary-hydrothermal |
|--------------------------|------|------------------------------|-----------------------|--------------------------|
|                          |      | Spodumene-bearing pegmatites | –                     | Li-rich Salars           |

|                                                                                     |             |                                                                                           |                                                               |                                                                        |                                                                                                                 |                                                       |                                                            |                       |                                                                              |
|-------------------------------------------------------------------------------------|-------------|-------------------------------------------------------------------------------------------|---------------------------------------------------------------|------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------|-------------------------------------------------------|------------------------------------------------------------|-----------------------|------------------------------------------------------------------------------|
| (current reserves and resources)                                                    | Ore mineral | Spodumene                                                                                 |                                                               | —                                                                      |                                                                                                                 | Brine (Dissolved Li as LiCl)                          |                                                            |                       |                                                                              |
|                                                                                     | Examples    | <i>Greenbushes (Australia), Manono (DR Congo), Whabouchi (Canada), Barroso (Portugal)</i> |                                                               | —                                                                      |                                                                                                                 | <i>Atacama (Chile), del Hombre Muerto (Argentina)</i> |                                                            |                       |                                                                              |
| Unconventional ore deposit (some of current resources and possible future reserves) | Type        | Petalite-Lepidolite <sup>1</sup>                                                          | High-Phosphorus Rare-element granites                         | Greisen developed in rare-element granite                              | Hydrothermal veins and alteration                                                                               | Li-bearing clays associated to volcanism              | Li-bearing clays associated to evaporites                  | Jadar-type            | Li-rich geothermal brine                                                     |
|                                                                                     | Ore mineral | Petalite and/or Lepidolite <sup>1</sup>                                                   | Lepidolite <sup>1</sup> , amblygonite-montebrazite            | Zinnwaldite <sup>2</sup> , Lepidolite <sup>1</sup>                     | Amblygonite, Tosudite / Li-rich muscovite, Lepidolite <sup>1</sup> , zinnwaldite <sup>2</sup>                   | Hectorite, Li-bearing smectites                       | Hectorite, cookeite                                        | Jadarite              | Li-rich Brine                                                                |
|                                                                                     | Examples    | <i>Lousas, Gonçalo (Portugal), Chedeville (France)</i>                                    | <i>Beauvoir (France), Argemela (Portugal), Yichun (China)</i> | <i>Zinnwald (Germany), Cinovec (Czech republic), Chavence (France)</i> | <i>Takatama (Japan), Bekogorskoe (Russia), Le Châtelet (France), San José (Spain), Argemela mine (Portugal)</i> | <i>Clayton Valley (USA), Moldova Noua (Romania)</i>   | <i>Dauphiné black schists (France), Rhassoul (Marocco)</i> | <i>Jadar (Serbia)</i> | <i>Buntsandstein formation (Germany &amp; France), Gwennap district (UK)</i> |

This type of deposit is strongly interesting for its generally high-grade lithium content ( $\geq 1\%$  Li<sub>2</sub>O) 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, 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 lithium-rich pegmatites (Figure 4). This class contains strong enrichments in lithium, tantalum and tin and variable enrichments in rubidium, caesium, beryllium and tungsten. The Li concentration is about 0.5 to 1% Li<sub>2</sub>O, hosted mainly 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 et al., 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 primarily occur close to the surface and are frequently spatially associated to and show strongly restricted volumes of magma, typically less than 1 km<sup>3</sup>.

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 (Figure 4) result from a high-temperature hydrothermal dynamic alteration of magmatic potassium-felspar, plagioclase and biotite (if any) into a porous muscovite ± quartz assemblage generally located in the upper part of granite intrusion, e.g. (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 et al., 2005; Launay et al., 2019; Štemprok, 1987) or may form up to 100-m thick units with irregular to sheet-like bodies.

Some rare-element granites (Cerny et al., 2005) are favourable lithologies for developing such deposit types, whereas geochemically less evolved granites appear to be unrelated with significant Li endowment. (Breiter et al., 2017) describe magmatic evolution of Cínovec rare-metal granite magmatic evolution of the late Variscan volcano-plutonic system. The granite is slightly peraluminous, enriched F, Li, Rb, Cs, Nb, Ta, Nb, Sn, W, Sc and U. The granite cupola hosts a greisen-type Sn-W-Li deposit with Li levels that varies from 0.17 – 0.25 % (maximum 1.8 % Li). According to (Gourcerol et al., 2019) and references therein, the Li<sub>2</sub>O content in the greisen around the world-class Panasqueira W deposit (Portugal) is only about 732 ppm, whereas Li<sub>2</sub>O values from Li-rich greisens are in the range of 80 - 3100 ppm. 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.

This type of deposit is of great interest due to its unusually 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-intensity magnetic separation (dry or wet) seems to be optimal for zinnwaldite separation.



## **Sedimentary-hydrothermal**

This group encompasses various types and styles of lithium mineralisation 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. The main recognized Li-mineralisation are 1) Li-bearing clays (hectorite) associated with volcanism; 2) Li-bearing clays associated with evaporitic sequence or arid sedimentary conditions (Figure 3); 3) Jadar-type (Figure 4), and 4) Li-rich geothermal brine.

The typical example of a hectorite deposit is Clayton Valley (Nevada, USA). According to (Munk et al., 2016) and the references attached, the Clayton valley is an arid closed basin surrounded by a basement including intrusive granites and a metamorphic core complex that partly controls the thickness of the basin via an important ductile to a brittle normal fault. The felsic volcanism (rhyolites, silicic tuffs) located along the basin and interbedded within lacustrine sediment have  $\text{Li}_2\text{O}$  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  $\text{Li}_2\text{O}$ ). Lithium-rich brines are also present in the basin. The lithium is presumed to come from the alteration of felsic volcanics by both magmatic and geothermal fluids and the surrounding basement and then concentrated in the basin by evaporation. Li-bearing clays and Jadar-type deposits are very interesting for their generally high-grade lithium content ( $\geq 1\% \text{Li}_2\text{O}$ ) and high ore tonnage. 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 to enable lithium extraction from jadarite and/or hectorite to produce high-grade lithium.

## **Lithium bearing bauxite**

Bauxite deposits can contain various amounts of lithiophorite, cookeite and tosudite (Li-rich gibbsite) (Nishiyama et al., 1975). Lithiophorite is the most common Li-bearing manganese oxide mineral in karst bauxites. It occurs in several localities, such as the Halimba, Fenyőfő, and Kincsesbánya deposits in Hungary, where aluminium and gallium in bauxite deposits were exploited during the 1950s until recently (Anderson, 2012). The presence of lithiophorite and local cookeite reflect Li enrichment, though this is not systematically evaluated. However, values up to 0.53%  $\text{Li}_2\text{O}$  within bauxite are known from China (Wang et al., 2019) and the USA (Tourtelot & Brenner-Tourtelot, 1977). Due to insufficient data, it is a challenge to assess the potential of bauxite for lithium; moreover, the lithium recovery from bauxite needs to be evaluated.

## **Unclassified**

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



### 3.1.3 Metallogenic provinces

The mineral prospectivity results and the distribution of lithium deposits and occurrences allowed us to define the 25 metallogenic provinces (Table 6). The Magmatic and magmatic-hydrothermal lithium mineralisation form numerous provinces. These 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 the extensional tectonic setting and arid climate during the Miocene (e.g., Jadar deposit, Pannonian basin); and 3) in Mesozoic-Paleogene bauxites developed on the Pelagonian metamorphic massif (e.g., Hungary, Greece).

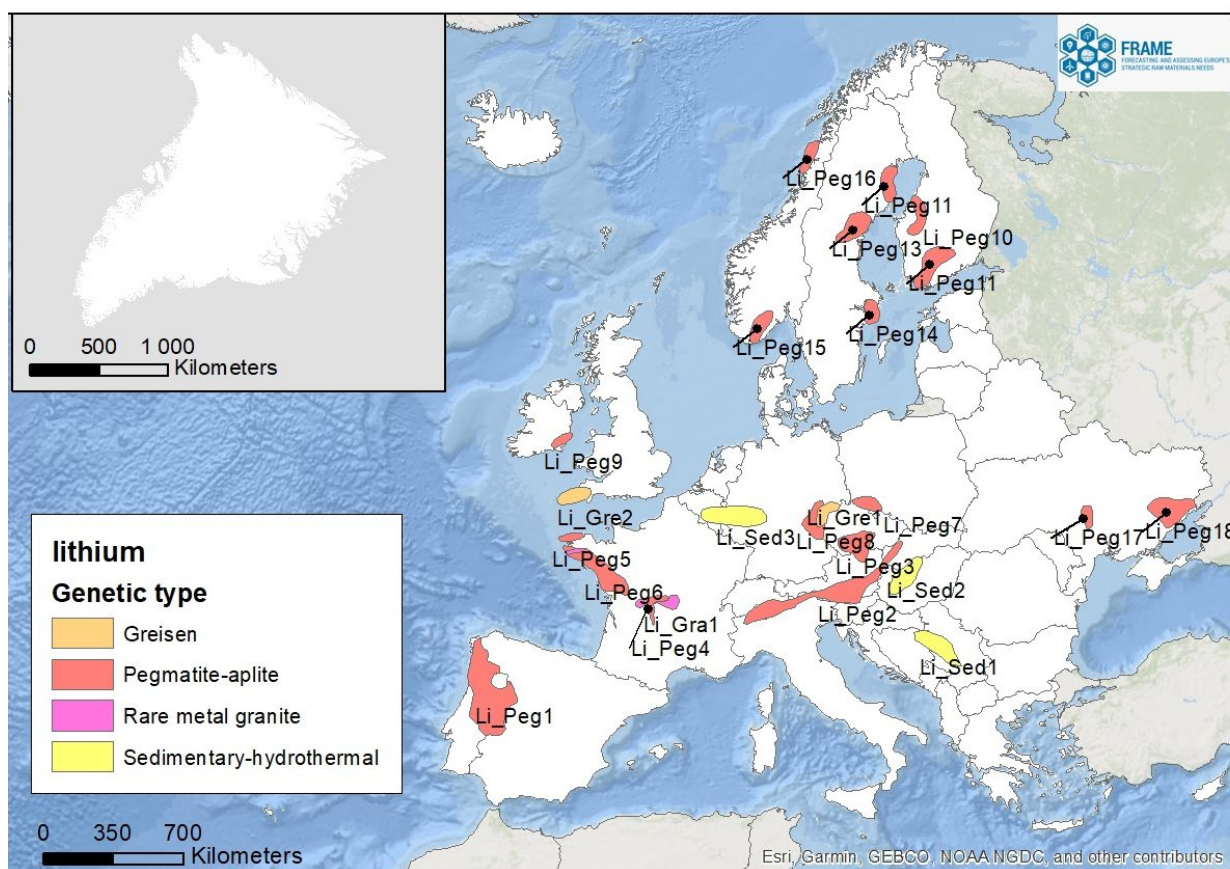


Figure 5. The main metallogenic provinces for lithium in Europe according to the genetic type.

Table 3. 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-Millevalches 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 kilometre-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 et al., 2012). Contacts with the 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 and granite intrusions (e.g., Gonçalo, Ambazac).



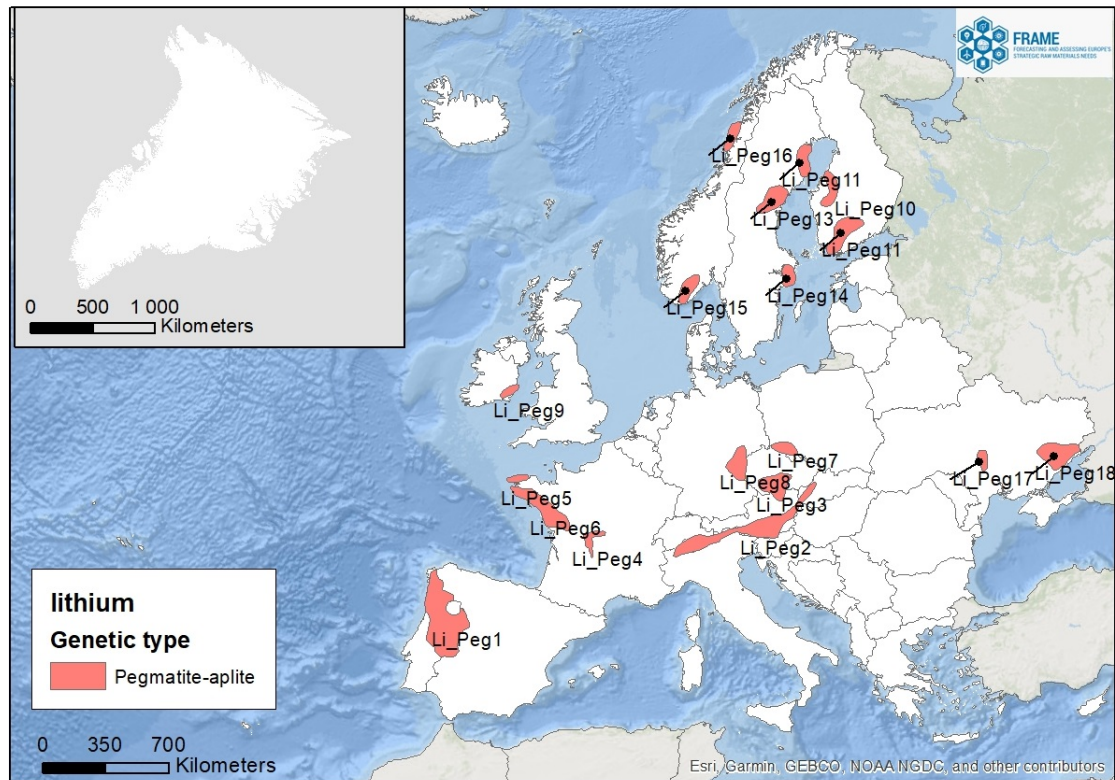


Figure 6. Main metallogenic provinces for lithium-bearing pegmatites-aplites in Europe.

In the **Ukraine**, several fields 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-Tashlykyskiy pegmatite province** (Li\_Peg17) in the centre of Ukraine, which is represented by three steeply-dipping pegmatite bodies (550 m long, 60 m in thickness, grade 1.25%  $\text{Li}_2\text{O}$ ). In this province, the resources of the **Nadiya** spodumene-pegmatite are estimated to 728,896t  $\text{Li}_2\text{O}$ . In the east of Ukraine, the **Shevchenkivske pegmatite province** (Li\_Peg18) contains several spodumene-bearing pegmatites like the **Shevchenkovskoe** deposit (resources of 69,960 t  $\text{Li}_2\text{O}$ ).

In **Finland and Sweden**, the prospective lithium-rich pegmatites are associated with the Svecofennian orogen (1.92-1.77 Ga). Significant lithospheric thickening during the orogeny leads to local migmatisation and the formation of S-type granites and pegmatite fields in Southern Finland and Central Sweden. Lithium mineralisation is emplaced in metasedimentary and metavolcanic units along major faults and shear zones between 1820 and 1775 Ma (Alviola et al., 2001; Romer and Smeds, 1994; Romer and Smeds, 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  $\text{Li}_2\text{O}$ ), **Syväjärvi** (reserves of 20,709 t  $\text{Li}_2\text{O}$ ), **Länttä** (reserves of 9,262.20 t  $\text{Li}_2\text{O}$ ) and **Outovesi** (reserves of 2,397.60t  $\text{Li}_2\text{O}$ ) 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 centred on the Vammala migmatite belt. Lithium-bearing pegmatites

(petalite/spodumene **Luolamaki**, **Hirvikallio** (resources of 2,685 t Li<sub>2</sub>O) and **Kietymaäki** 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., Härnö, 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) hosts the smallest potential. This province is hosted by the Sörmland basin. According to (Romer and 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.

Variscan pegmatites represent another very prospective target. The European Variscan orogen results from the Late Paleozoic convergence and collision between the Gondwana (south) and the Laurasia-Baltica (north) megacontinent and involves several intermediate microcontinents and closures of oceanic domains (Matte, 1991; 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 et al., 2005). These events appear to have been diachronous throughout the Variscan orogeny. According to (Romer and 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**, e.g. (Cuney et al., 2002b), appears a strong example of this phenomenon. The most important Variscan lithium-bearing pegmatite province is **the Galicia – Centro-Iberian pegmatite province (Portugal and Spain)** (Li\_Peg1). This province comprises more than 20 major Li-pegmatite field reviews (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-Trás-os-Montes zone), intrusions are mainly emplaced in the nappe of the para-autochthonous schists and sometimes up to the nappe of the lower allochthon (eg. **Lalín** spodumene-pegmatites, (Fuertes-Fuente et al., 2000). The most important pegmatites field for lithium seems to be, in Portugal, the **Barroso-Alvão** (**Barroso** (resources of 241,000 t Li<sub>2</sub>O), **Sepeda** (resources of 103,000 t Li<sub>2</sub>O), **Adagoi** spodumene pegmatites) and **Gonçalo** pegmatite fields (**Alvarrões** with resources of 51,069t Li<sub>2</sub>O) 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, occasionally with petalite-lepidolite dykes that were exploited in the 19<sup>th</sup> century (**Chedeville** pegmatites (Raimbault, 1998) with an ore production of 7078t between 1929 and 1938). To the west, in the Armorican massif, lithium mineralisation is restricted to the thickened Variscan domains (Ballèvre et al., 2009), the Léon block in the northwest and the South Armorican domain along the southern coast. The **South Brittany pegmatite province** (Li\_Peg6) includes several pegmatites fields over a large surface. Some of the pegmatites are mineralised 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-Montebrazite, 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 appear to be coeval with two metamorphic-anatectic events (Melleton et al., 2012).

**In the 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 Li<sub>2</sub>O. 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 occur as 500m-long dykes within amphibolite-grade micaschist on the NE side of the Conțu mount (Popescu et al., 2013).

**In Austria**, pegmatites are not Variscan but Lower Permian in age. **Austroalpine pegmatite province** (Li\_Peg2) is composed of thousand pegmatites and extend 400km, from the north of Torino up to the south of Vienna (Schuster et al., 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 Li<sub>2</sub>O*). These pegmatites appear to be generated by anatexis from mica schists and paragneisses at upper amphibolite to granulite facies (Knoll et al., 2018; Schuster et al., 2019) coeval with lithospheric extension, causing



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

Apart from the orogens mentioned above that are favourable for mineralisation, it appears that other orogens are not favourable to the presence of mineralisation except in certain localities. The absence of mineralisation is the case for the Sveconorwegian orogeny (**Glomfjord** and **Setesdal-Bamble-Nissedal pegmatite provinces**). Indeed, despite several thousands of pegmatites, mainly of Niobium-Yttrium-Fluor type (Müller et al., 2017), only a few contain significant amounts of lithium and 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, economic lithium pegmatites cannot be ruled out. Globally, the Caledonian orogeny (ca 475-380 Ma) seems poor in lithium mineralisation, except for Ireland. Indeed, the ca. 412 Ma **Leinster LCT pegmatite province** (Barros et al., 2020) and references enclosed) includes pegmatite fields where spodumene-rich pegmatites occur (e.g., **Aclare** with resources of 8,550t Li<sub>2</sub>O and **Molysha** 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-montebbrasite) and Li-micas (lepidolite and Li-muscovite). Despite their small size (<1 km<sup>3</sup>) they host large, disseminated mineralisation; for example, the **Beauvoir** Li resources are estimated to 375,300t Li<sub>2</sub>O (Gloaguen et al., 2018). They are emplaced close to the surface 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 Li<sub>2</sub>O), composed of Li-bearing hydrothermalized schists cross-cutted by a quartz-amblygonite-Montebbrasite veins system (Pesquera et al., 2020).

**In France**, the most important target for lithium-rich granites is the **rare element belt** (Cuney et al., 2002a), 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 e.g. (Cuney et al., 1992; Raimbault et al., 1995)) with resources of 375,300t Li<sub>2</sub>O, and the **Richemont** rhyolite (Raimbault and 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 Li<sub>2</sub>O), (Gloaguen et al., 2018) and references enclosed, showing a chemical composition close to the Beauvoir granite.



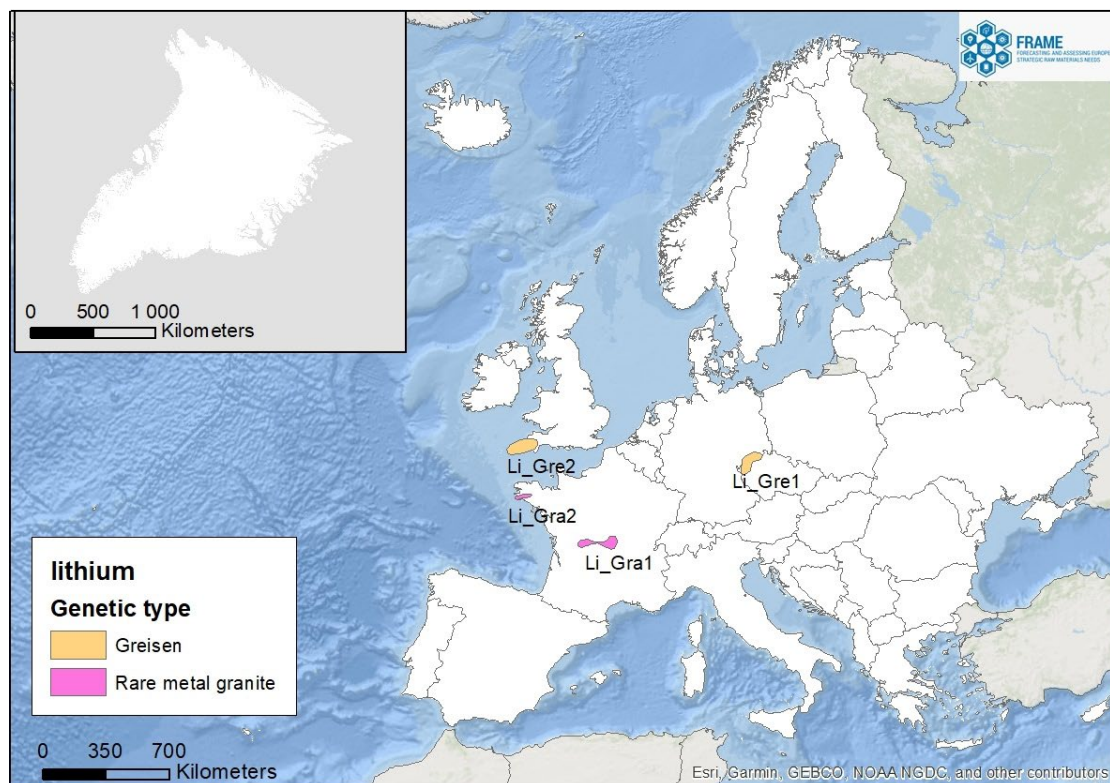


Figure 7. Main metallogenic provinces for lithium-bearing granites and greisens in Europe.

In 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 and Noronha, 1996; Michaud et al., 2020) with lithium resources estimated to 49,950 t Li<sub>2</sub>O.

In the United Kingdom, the **Saint Austell** granite contains a large volume of disseminated Li-bearing micas (Zinnwaldite, Lepidolite) with (too optimistic?) resources estimated at 2,921,631.77 t Li<sub>2</sub>O (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 forming 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-montebrasite 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 Li<sub>2</sub>O content in the greisen around the world-class Panasqueira W deposit (Portugal) is only about 732 ppm, whereas Li<sub>2</sub>O 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 **Cínovec** greisen with Li resources estimated to 2,921,631t Li<sub>2</sub>O and the **Zinnwald** greisen with Li resources estimated to 124,959.69 t Li<sub>2</sub>O (Gourcerol et al., 2019). Krásnov and Horní Slavkovin the Western Erzgebirge area represent the second region in the Czech Republic with 41.199 kt of Li metal.

Secondary deposits, former mining wastes, contained in tailings are estimated to contain ca 8.5 kt Li metal.

**In the United Kingdom**, the main greisen mineralisation (Brown et al., 2016)) is 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, laterite 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.

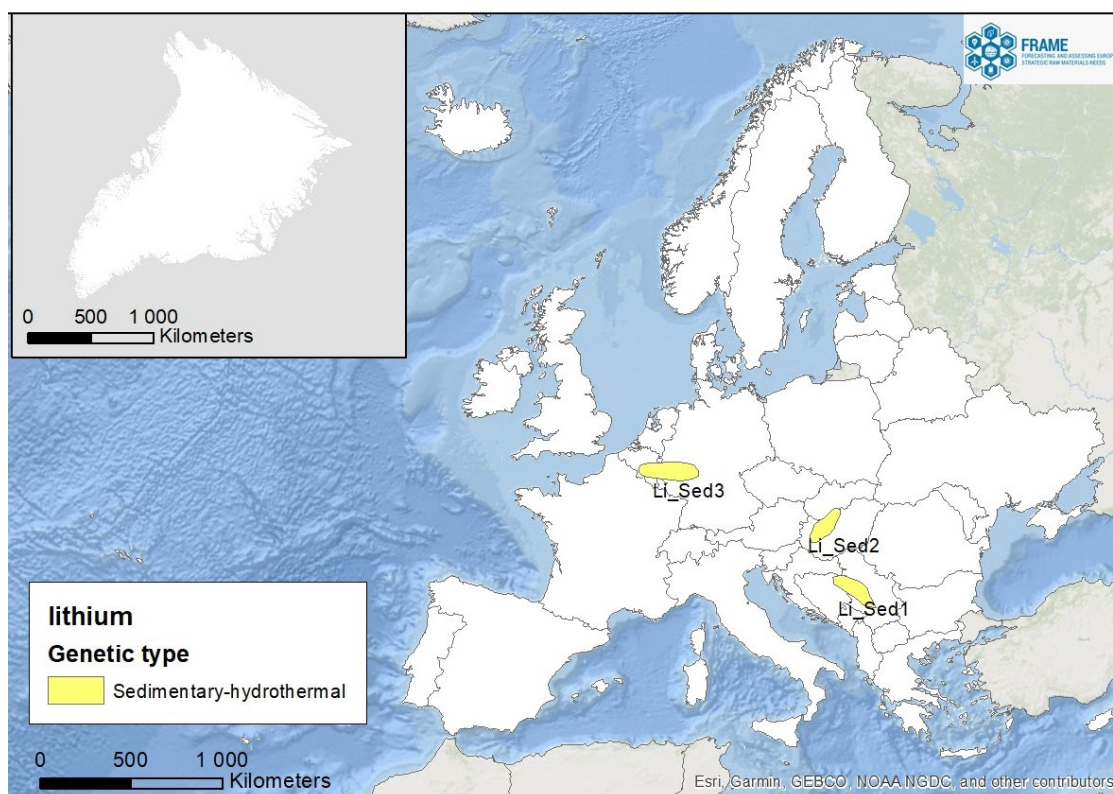


Figure 8. Main metallogenic provinces for sedimentary-hydrothermal lithium mineralisation in Europe

**In Serbia**, the **Jadar** deposit (resources of 2,524,020t Li<sub>2</sub>O) 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 series close to a basement where granites and spodumene

pegmatites occur (Lazić et al., 2009), suggesting local lithium enrichment in the basement. Nevertheless, the jadarite precipitation process is poorly constrained. Other 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 and Mindszenty, 1987) and in Jurassic to Cretaceous bauxites from Greece. The main Li-bearing minerals 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 characterised into two types: Fe-Mn reddish siliciclastic rocks and Mn-Fe lenses or layers. In Fe-Mn rich rocks, the presence of lithiophorite is secondary and related to fluid circulation (Nicholson and Anderton, 1989). Despite the presence of lithiophorite, the amount of lithium is generally low. The first group of deposits is found 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 et al., 2011; Waldron et al., 2011). The second group is mainly found in Hungary, where the **Eplény** and **Urkut** Mn deposits are Jurassic in age (Polgári et al., 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 was derived from chemical weathering of continental crust and was originally concentrated in siliciclastic or carbonate rocks.

## 3.2 Cobalt

Cobalt occurs as a trace to minor constituent in many different ore deposit types and can be a significant by-product in some deposit types. Typical grades vary from <0.01 % to 0.1 %, in more enriched deposits between 0.1-0.3 % and in more rare cases grades can be up to 1 %. Cobalt forms several ore minerals, often combined with other metals such as Ni and Fe, together with S and As or as minor-trace components in Ni and Fe sulphides. It also forms secondary minerals such as hydroxides and oxides and carbonates (Slack et al., 2017).

### 3.2.1 Geological processes

Cobalt can be enriched by a variety of geological processes in different environments ranging from magmatic to hydrothermal to supergene processes, in which it can be related to several other metals such as Ni, Cu, Fe and even Au. In many cases, the exact factors governing Co mobility in various ore-forming processes is poorly understood as the focus of research has been on the main commodities.



Cobalt is a ubiquitous minor constituent in magmatic Ni-Cu deposits. These types of deposits are always hosted by a distinct type of magmatic formations, i.e., relatively MgO-rich intrusions or extrusions (lava flows). Cobalt grades vary with Ni-grades, typically from 0.01 to 0.1 % Co.

Hydrothermal processes, where metals are transported by saline water-based fluids, generate a wide variety of different ore deposits in a variety of geological settings. Deposit types include volcanogenic sulphide deposits originally formed at sea floor (VMS deposits) by heated sea water circulating in the oceanic crust in areas of tectonic and magmatic activity such as mid-ocean spreading centres (e.g. the Mid-Atlantic Ridge) and volcanic island arcs (e.g. western Pacific Ocean). Cobalt grades are generally low and typically 0.01-0.03 %, with some enriched deposits, e.g., in Finland. The Outokumpu-type deposits contain 0.1-0.24 % Co (Eilu, 2012). The sediment-hosted stratiform Cu-Co deposits form in sedimentary basins from basin-derived fluids during lithification and tectonic-metamorphic events. Globally, these types of deposits are the most important sources of Co, especially in DRC, but relatively uncommon in Europe where they contain only low Co-contents. Deposits in DRC contain 0.2-1% Co; the global average is 0.3 % Co (Slack et al., 2017). 5-element and other vein-type deposits may contain %-level Co concentrations but are generally small deposits. They are derived from fluids generated during metamorphic events and can be found throughout southern-central Europe. Other hydrothermal deposits that can contain minor-moderate Co include Fe-Cu-Au (IOCG) deposits, skarn deposits (Cu-Fe), certain Cu-Co-Au deposits and orogenic Au deposits (Slack et al., 2017).

Supergene weathering processes occurring on mafic and especially ultramafic Mg-rich rock formations can form lateritic Ni-Co deposits. These are formed by surface waters transporting and depositing metals (Fe, Ni, Co) downwards during weathering process in subtropical-tropical climates. Large, Co containing lateritic Ni deposits occur also in Europe, e.g. In the Balkans and Greece, with reported Co-grades from 0.03 to 0.15 % (Horn et al., 2021).

The black shale hosted Talvivaara Zn-Ni-Cu-Co deposit (Sotkamo mine) represents a rare type of metal-enriched black shale type deposit with a Co grade of 0.019 % with a contained metal content of 278 000 t (Terraframe, 2018).

### 3.2.2 Deposits and metallogenetic provinces

Based on the distribution of Co deposits and occurrences in Europe, a total of 34 metallogenetic provinces have been delineated (Fig. 9), most of which cluster in the Nordic countries (Finland, Norway and Sweden) with few, smaller scattered provinces across southern and central Europe. Larger lateritic provinces are found in the Balkans and Ukraine.

Broadly, the main cobalt metallogenetic provinces are:

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



The Fennoscandian Co-occurrences have highly variable ages ranging from late Archean (2750 Ma) to Palaeozoic (~440 Ma) and represent various deposit styles. Deposits in **Finland** occur throughout the country, with magmatic Ni-Cu-Co deposits occurring along two belts in southern and central Finland, with 11 past-producing mines. The most significant deposits are the past-producing Hitura, Kotalahti and Enonkoski (Laukunkangas) mines, each with >10 Mt of ore. Exact cobalt production is known only from Enonkoski with 2100 t of Co (Pöyry and Isomäki, 1991). The Kevitsa Ni-Cu-Co-PGE deposit in northern Finland is currently under mining, producing between 500-600 t of Co per year, containing 30 000 t of Co (reserves+resources). Historically, the most important Co deposits have been the Outokumpu-type volcanogenic Cu-Zn-Co-Ni deposits. The Outokumpu deposit is the largest (28.5 Mt) and produced over 50 000 t of Co between 1910-1989 (Peltonen et al., 2008). Outokumpu-type deposits cluster in a relatively restricted area in eastern Finland. Another cluster of deposits, representing Kuusamo-type Au-Co-Cu deposits, occur in the eastern part of northern Finland. Recent review of the largest Juomasuo deposit indicate up to 15 000 t of contained Co (Latitude 66, 2021). The black shale hosted Talvivaara Ni-Zn-Cu-Co is another active mine (Sotkamo mine) in Finland producing cobalt. The actual production is unknown, but it is estimated to be 500 t of Co per year. This giant deposit contains ~1500 Mt of ore with 290 000 t of contained Co. In addition to these deposits, some of the Finnish Fe-Cu-Au (IOCG) deposits have significant contained Co tonnage (e.g., Hannukainen ~30 000 t).

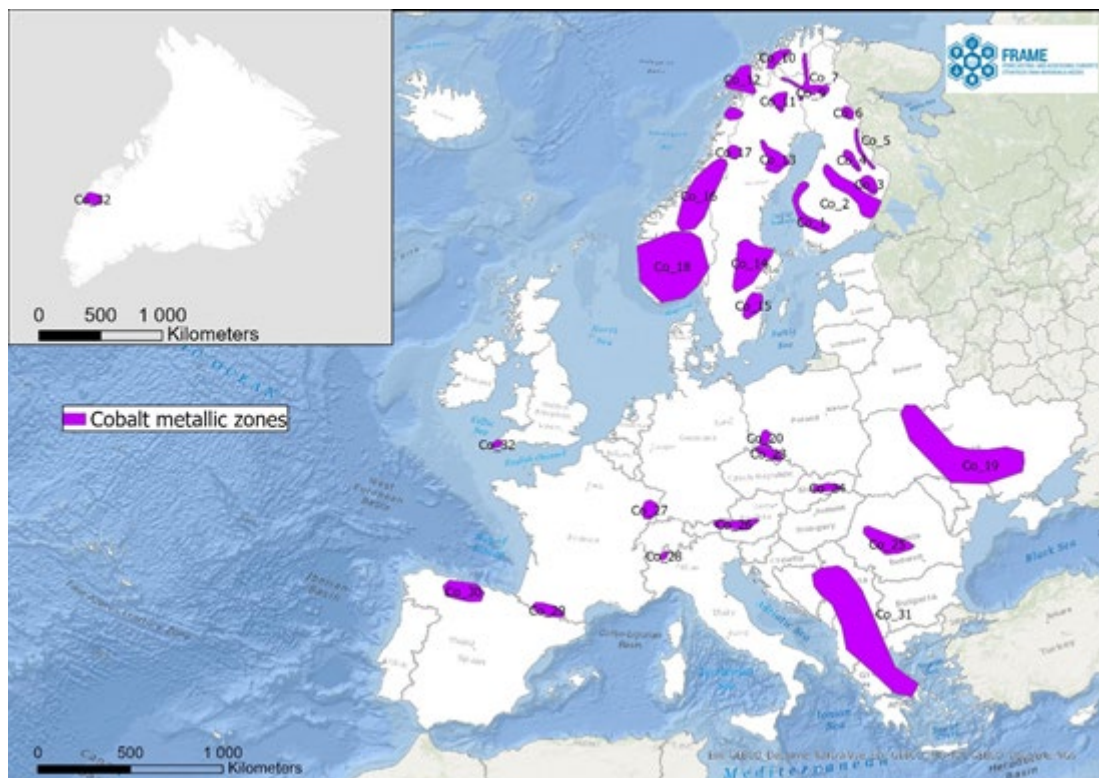


Figure 9. The metallogenic provinces of Cobalt.

Although **Sweden** has a long mining history, the country has produced relatively low amounts of cobalt. Historic production from the 1700s to the beginning of the 1900s mostly came from small Cu-Co mines in southern Sweden, such as Vena orefield. The Vena orefield was the most important Co producer in Sweden, with 0.5 Mt of ore extracted (grade unknown), mainly in the 1800s. The Los Cu-Co and Kleve Ni-Cu-Co mines also produced some Co (the 1700s to early 1900s). Magmatic Ni-Cu-Co deposits occur in the Lappvattnet area in central-northern Sweden as well as in the Swedish Caledonides, including the Njeretjakke Ni-Cr-Co deposit (38 Mt with 0.015 % Co). In Northern Sweden, the 7.7 Mt Kiskamavaara IOCG deposit contains some 2600 t of cobalt. (Hallberg et al., 2012).

**Norway** hosts a relatively large number of Co-containing deposits, most of which represent magmatic Ni-Cu-Co and volcanogenic Cu-Zn deposit types. Historic Co-production came from the sediment-hosted Cu-Co Skuterud (Modum) deposit (20 000 t) and the Flåt Ni-Cu mine (2400 t) from the late 1700s to the mid-1950s. Most magmatic Ni-Cu-Co deposits occur as a cluster of small deposits in southern Norway, many of which have been mined in the past, such as the Ertelien, Romsås and Hosanger. Another cluster of deposits occurs in central southern Norway in the Jotunheimen area. The Stormyra and Dalen deposits contain ~1 Mt and 5 Mt with 0.04 % and 0.02 % Co. In northern Norway, the Råna (Bruvann) Ni-Cu-Co deposit was mined between 1989-2001 and has a resource of ~9 Mt with 0.03 % Co (2700 t contained Co). Norway hosts a lot of well-known volcanogenic (VMS) Cu-Zn deposits, many of which have been mined until the 1980s. Many of these are known to contain minor Co, such as Lokken, Ny-Sulitjelma, Charlotta and Sagmo (0.013-0.07 % Co). VMS deposits occur throughout Norway, again often in clusters. (Sandstad et al., 2012).

In **Greenland**, cobalt is known to occur in small VMS-style occurrences in SE part of the country (Illukulik) and numerous Ni-Cu-Co occurrences are located in the Manitsoq area in the SW coast (Stensgaard et al., 2017).

In the **United Kingdom**, cobalt mainly occurs as vein-style mineralisation associated with the tin granite deposits of Cornwall with historic Co-production of a few hundred tonnes of ore. Historic production is also reported from Foel Hiradugg in Wales (240 t) and Silver Glenn and Hilderston in Scotland from vein-type mineralisations (Horn et al. 2021) (Petavratzi et al., 2019).

In southern and central Europe, clusters of mostly small Co occurrences extend from Spain to France, northern Italy, Austria, southern Germany, SW Poland, Slovakia, and Romania. A cluster of Co-bearing vein type and sediment-hosted deposits occur in the Cantabrian Mountains in NW **Spain**. Some of these deposits have been mined since Roman times, e.g. Texeo Mine, which produced ca. 200 000 t of ore with estimated Co content of 1-3 % between 1947-1956 (Loredo et al., 2008). Cobalt deposits occur also in the Betic Cordillera in SE Spain (e.g. Cerro Minado). The magmatic Aquablanca Ni-Cu-Co deposit in southern Spain was mined between 2005 and 2016 and has a mineral reserve of 6 Mt at 0.02 % Co (0.6 % Ni and 0.5 % Cu) (Sánchez-García et al., 2013). In **Italy**, cobalt deposits occur mainly in the Alpine region of Piedmont, where the deposits are related to mafic-ultramafic intrusions and pipes of the Ivrea-Verbano Zone (Horn et al., 2021).



Some of these deposits have been mined in the past, but very little is known about grades and tonnages. Some historic estimates indicate Co grades between 0.15 to 0.3 % (Alligator Energy Ltd, 2018). A cluster of polymetallic vein-type are known from NE **France**, and cobalt was produced from the Sainte Marie Aux Mines and Kruth. Vein-type deposits also occur in the western Alps, and cobalt was extracted from the Challanches silver mine. In southern France, in the Pyrenees, cobalt occurs in SEDEX-type Pb-Zn deposits as stratabound and vein mineralisation, with some historic production in the 18<sup>th</sup> century (Horn et al. 2021). In **Austria**, sediment-hosted and VMS style deposits occur in the Leogang and Zinkwald mining districts, where cobalt was mined until 1959 (Horn et al. 2021). Polymetallic vein-typed and magmatic Ni-Cu-Co occurrences are known from the Schwarzwald and Erzgebirge districts in **Germany**, extending to the **Czech Republic** in the East. Several polymetallic vein-type deposits occur in central **Slovakia**, most important being the Dobsina and Kolba in the western Carpathians, which were also mined in the 1800's. Recent drilling by European Cobalt has identified Co grades up to 1.92 % (European Cobalt, 2019). SW **Poland** has a cluster of Co bearing sediment-hosted Cu-Co deposits, various vein-type mineralisations (Sudety Mountains) and lateritic Ni-Co deposits. Historic cobalt mining took place at the Przeczница tin mine and also from the historical Gierczyn and Krobica tin mines. A rarer Co-deposit type is represented by two magmatic Fe-Ti-V deposits in NE Poland (Horn et al. 2021). In **Romania**, cobalt occurs in skarn and polymetallic vein-type deposits in southern Carpathians. The eastern and western ophiolite belts extending from Turkey through **Greece** and the **Balkans** host many significant lateritic Ni-Co deposits. Several deposits in Greece were mined until 2020, and there are some operating mines in the Balkans (Albania, Kosovo and North Macedonia). These mines produce ferronickel, an iron-nickel compound used for steel production, but no cobalt production has been reported. However, a presentation by Greek ferronickel producer Larco indicates that their ferronickel contained 0.75-1.0 % Co (Apostolikas and Kountourellis 2014). The data presented by Horn et al. (2021) indicates significant Co resources hosted in these deposits. Historic estimates include Mokra Gora, Serbia: 360 000 t of contained Co, Rzanovo, North Macedonia: 25 000 t of contained Co.

### 3.3 Graphite

The geology of graphite is much simpler compared to that of lithium and cobalt. It is a single element and a single mineral. However, the individual occurrences vastly differ, which is mainly related to the difference in the primary host rock for the graphite and its metamorphism and deformation.

#### 3.3.1 Geological processes

The industry divides natural graphite and the occurrence types of graphite into the following groups. We refer readers to (Harben and Kužvart, 1997) for their review.

- A) Flake graphite: Flake graphite is graphite formed in metasedimentary rocks of high metamorphic grade. These deposits are characterized by the presence of

flakes of individual graphite crystals in variable grain size. Traditionally the coarser flakes yield more valuable ore, and the carbon content can vary from 2-3 % up to more than 30 %. The metamorphic grade of the graphite bearing rocks is either high amphibolite or granulite facies.

- B) Amorphous graphite: The term amorphous graphite is misleading, and micro crystalline graphite is more an accurate description. This graphite is formed from coal deposits altered by contact metamorphism or from low metamorphic grade organic-rich shales. This ore type typically occurs as masses of graphite rich rock. In general, and worldwide, amorphous graphite deposits have higher carbon (graphite) content than flake graphite deposits (Robinson et al., 2017). In principle, only the graphite crystal grain size and degree of metamorphism distinguishes amorphous and flake graphite deposits.
- C) The vein or lump graphite: This is a particular type of graphite deposit that is only mined in Sri Lanka. They are shown to be formed by processes that involve the interaction of CO<sub>2</sub>, CO, CH<sub>4</sub> and H<sub>2</sub>O during granulite facies metamorphism. Although these deposits are only mined in Sri Lanka, their occurrence is not uncommon (Luque et al., 2014).

Worldwide amorphous graphite deposits are the source for about 40 % of the world's production. 58% comes from flake graphite deposits and 2% from veins deposits (Olson, 2020). In Europe, flake graphite is produced from mines in Norway and Ukraine and amorphous graphite from two mines in Austria. Graphite occurrences are, in general, much less investigated than metals. Hence, with a relatively high proportion of the graphite occurrences in Europe being unclassified, the lack of detailed studies make it impossible to group them into either flake- or amorphous deposits.

The graphite crystal and flake size is important for many end uses. Generally, the coarser the flake size and higher purity (carbon content) the high price for the end product. In exploration flake graphite deposits are therefore preferred.

Most of Europe's and the world's graphite occurrences have their carbon and graphite from a biogenic source. Whether the graphite crystallize to form a flake or amorphous graphite deposits is determined by the subsequent metamorphism. In general, high grade amphibolite or granulite metamorphism creates flake graphite deposits and lower metamorphism result in an amorphous type. However, it is not uncommon for a single mine to produce grain size fractions that are sold on the market for flake graphite and amorphous graphite, depending on the particle size of the carbon.

The scientific classification of graphite and carbonaceous materials is defined based on the crystallinity or the degree of crystalline ordering of the graphite crystallite. This is measured with XRD or by Raman spectroscopy. There is a gradual transition with increasing temperature from coal to semi graphite and graphite see (Beyssac and Rumble, 2014; Kwiecińska and Petersen, 2004)



### 3.3.2 Deposits and metallogenetic provinces

The graphite occurrences in Europe, cluster into 30 different provinces (Figure 10). 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, Bavaria & Bohemia in the Czech Republic
- 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 and largest deposit 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%. See (Gautneb et al., 2020b) for details. In addition to the present active mine, two adjacent deposits are under investigation by the producing company. (Mineral commodities Ltd, 2020; Mineral Resources Commodities Ltd, 2021).

In **Finland** about 30 occurrences has been exploited historically and about 20 of these are located within the present borders.

In the South-eastern Finland there are several small flake graphite occurrences such as Pertunmaa (5–10 wt% C), and Kärpälä (40 wt% C) at Mäntyharju, but due to their small size they lack commercial value. Showings of flake graphite are also known in the Lapland granulite belt and the Joutsijärvi area near Kemijärvi. The amorphous graphite deposits in Juuka, Kiihtelysvaara (29 wt% C) and Kolari contain several million tons of fine-grained graphite but the flotation tests yielded too low carbon contents for these deposits to be economic.

Finnish graphite deposits have been described by (Laitakari, 1925) which lists ~150 small flake graphite occurrences among Svecofennian mica gneisses. Kärpälä deposit in Mäntyharju was the biggest, from which a few thousand tons of graphite ore were mined (sorted ore was sold to England and Sweden).

In Finland, the best-known flake graphite deposits is Piippumäki at Pertunmaa 50km southwest from Mikkeli. Flake graphite occur disseminated in cordierite and garnet bearing mica gneiss, which also contains some pyrrhotite and pyrite. Graphite content

is generally 5-10 % . The deposit is 10-30 m thick and 500 m long. According to Rautaruukki Oy carbon content of the graphite concentrate is about 80 % and recovery 90%. An old graphite pit of Kärpälä (40% C) where compact graphite lens in mica gneiss is located 2 km NE from Piippumäki (Palosaari et al., 2020) and references therein.

The Joutsijärvi study area is located in the eastern part of the Central Lapland Granitoid complex, about 25 km east from Kemijärvi. The Joutsijärvi area, strongly granitized schist belt, was earlier GTK's exploration target for base metals and gold. Twenty-two (22) shallow diamond drill holes (656 m totally) and six deep diamond drill holes (625m totally) were drilled in magnetic and electromagnetic anomalies caused by iron sulphides and flaky graphite. Flaky graphite was noted, and beneficiation tests were made from selected samples. The preliminary tests showed that the quality of graphite is good. In this recent study drill cores were reviewed and more detailed mineralogical and chemical analyses on the flaky graphite schists. (Al-Ani and Sarapää, 2016).

In **Sweden**, there is potential for high-grade natural graphite deposits in Sweden. Graphite occurrences in central and northern Sweden, exclusively hosted by Palaeoproterozoic metasupracrustal rocks, include several key prospects of which at least two (Kringeltjärn-Woxna and Nunasvaara) are presently the focus of ongoing exploration and assessment. In terms of recent production, the Kringeltjärn-Woxna deposit was intermittently mined between 1996 and 2015 and forms part of a larger central Swedish graphite prospect containing three more deposits of substantial size (Mattamyra, Gropabo and Månsberg). there are 54 known graphite occurrences most of them in the Norrbotten area. There is a mixture of flake and amorphous graphite deposits.

The **Kringeltjärn - Woxna area** was investigated extensively in the 1990's. The deposit is presently held by Leading Edge materials and under care and maintenance. The resources are estimated to be 9.66 Mt grading between 8.35 and 10.68 (Reed, 2015).

The **Nunasvaara (Vittangi area)** consists of several graphite deposits Nunasvaara proper is the most known. The deposit is presently held by Talga resources, inferred reserves are 2.9 Mt with a grade of 28.1 %. (Lynch et al., 2016; Lynch et al., 2018).

In the **Masugnsbyen** area about 90 km south of Kiruna, several graphite occurrences have been known for a more than century (Geijer, 1918). The detail of investigation varies widely but indicate an area with future potential.



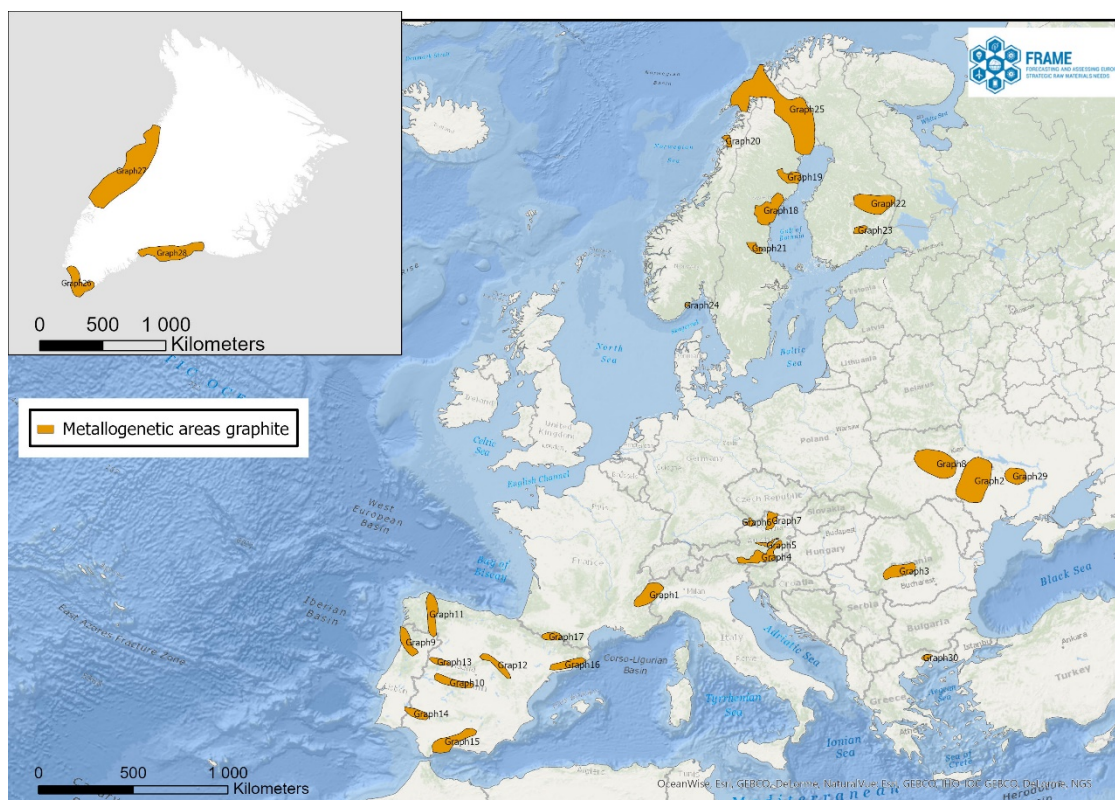


Figure 10 Graphite provinces in Europe

The graphite occurrences of **Ukraine** are all located on the Ukrainian 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%.

In **Greenland** there are 7 occurrences in the FRAME 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 **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 et al., 2017)

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 (Müller et al., 2016). Carbon content of the graphite bearing rocks can be very high up to 60% with a median of 38% (Schedl et al., 2016). At about 30 different sites, graphite was mined from 1895 until the last closed in 1994 (Hofbauer, 1995)

The north-western 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 (Sothorn Styria area)** (Graph4 on fig. 17) the area is divided 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 (Schuster et al., 2006)

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 migmatizations, 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.

The **Czech Republic** was one of the world's leading producers of graphite, but mainly due to the growing competition of cheaper and better-quality Chinese graphite mining closed in the Czech Republic. The underground mining of graphite deposits in southern Bohemia was terminated in the second half of 2003. In northern Moravia, underground



mining predominated in the early mining period, but a significant part of the ore recovered from the open pits. The last quarry of amorphous graphite was closed in 2008.

Graphite deposits of the Czech Republic are located in several varied groups of crystalline rocks: In the Český Krumlov and Sušice-Votice Varied Groups (southern Bohemia) in the Svatka Crystalline Unit (western Moravia) and in the Velké Vrbno Crystalline Unit (northern Moravia; Fig. 11). The following text describes typical deposits of the Český Krumlov Varied Group (Moldanubian Zone), Velké Tresné deposit in the Svatka Crystalline Unit, and the Velké Vrbno-Konstantin deposit of the Velké Vrbno Crystalline Unit. All graphite deposits in the Czech Republic originated through regional metamorphism of disseminated organic matter in sediments.

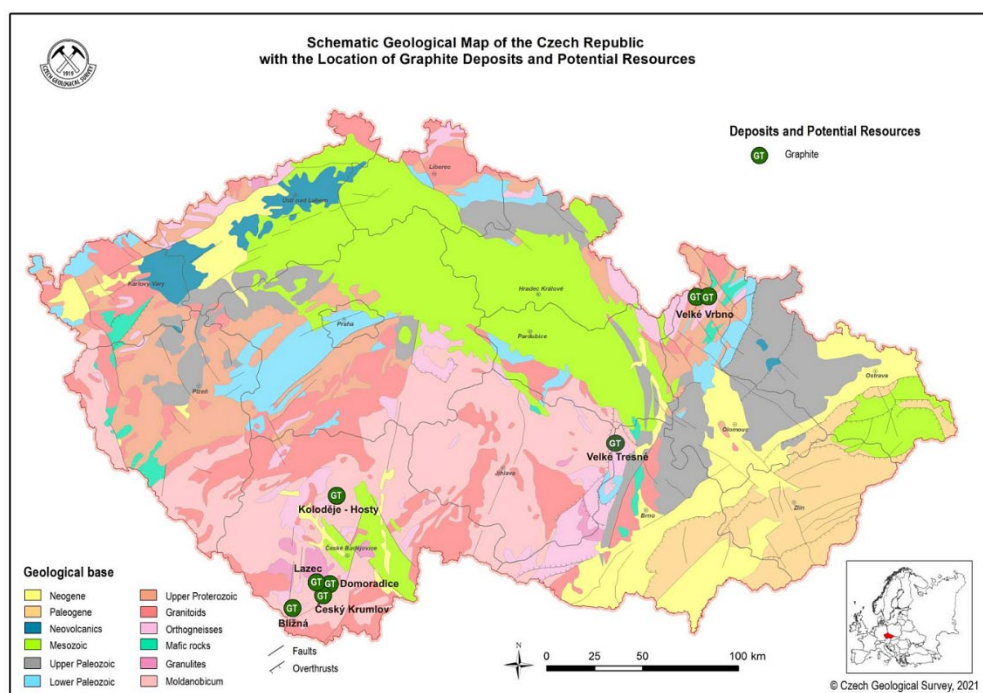


Figure 11 Schematic geological map of the Czech Republic with the location of the main graphite deposits and potential resources.

The total mineral reserves of graphite ore in the Czech Republic for the year 2019 registered in the Mineral Commodity Summaries yearbook (Starý et al., 2020) and approved by the Commission for Projects and Final Reports of the Ministry of the Environment of the Czech Republic reached 13 701 kt, which includes 4 110 kt of “amorphous” and 9 002 kt of “macrocrystalline” graphite ore. These reserves correspond to 589 kt of contained graphite.

The **Český Krumlov Varied Group (CKVG) (Southern Bohemia)** area forms a belt about 30 km wide which extends in the NE-SW direction and extends from the Austrian border and stretches further to the area of the Český Krumlov Town (Fig. 11). The rocks mainly comprise biotite gneisses and amphibole-biotite gneisses with intercalations of marble, and dolomites. (Kadounová, 1987). Metasediments are accompanied by different types of amphibolites (Romanová, 1989).

The length of mined graphite seams in Southern Bohemia varied from 100 m to 300 m, and the total length of deposits, including non-mined sections, ranged between 900 and

1000 m. The thickness of minable seams was usually between 1.5 m and 5 m, but the maximum thickness, for example, in the Bližná deposit, reached up to 25 m. The  $C_{\text{graph}}$  contents ranged between 10–20 wt. %, exceptionally up to 70 wt. %. The most important Lazec-Křenov deposit was mined underground until 2003. The deposit consisted of two graphite seams with several offsets. The ore consisted of crystalline graphite (flake size from 0.16 to 0.25 mm, exceptionally above 0.25 mm).

A geological survey and mineral exploration in the CKVG area in the second half of the 20th century included, in addition to a wide range of geophysical survey methods used, drifting of 1,500 meters of test pits, and approximately 10,000 meters of exploration galleries (SINE, 2021). At present, 9,381 kt of proven reserves of graphite ore are identified in this area. These reserves correspond to 1,593 kt of graphite mineral. At the same time, a total of 10,829 kt of graphite resources, including indicated resources, with an average of  $C_{\text{graph}}$  content of 15 wt. % (Starý et al., 2020).

*The **Velké Vrbno – Konstantin deposit (northern Moravia)*** is a deposit comprising seams of microcrystalline graphite with seams 3-6 metre thick and an average graphite content of 39%. The deposit was in production until 2008. Several other smaller deposits are known in the surroundings. (Tichý, 1983; Tichý and Voda, 1983).

In the ***Svratka crystalline unit of western Moravia***, two graphitic deposits (Velké Tresné and Mládkovo). These deposits contained up to 35% of carbonaceous material and up to 7 % of sulphur. The sulphur content is too high for the current quality requirements.



## 4. Future potential

When discussing the potential or future mineral resources potential, it is important to point out that a mineral deposit is just geological curiosity if no market or buyer exists. The forward-looking studies by the EU commission (European Commission, 2020a) predicts an about 3-fold increase in the consumption of lithium, cobalt and graphite. In this chapter, we summarise the areas where we believe the future potential is located.

### 4.1 Lithium

This study and past research (e.g., Gourcerol et al., 2019) strongly suggest that lithium is not rare in Europe. Thus, the main issue is mineral processing, not geology. Indeed, the future potential in Europe is very large or very narrow, depending on our ability to economically extract high-purity lithium from various Li-bearing minerals because conventional lithium deposits are not abundant in Europe. Nevertheless, many large to very large unconventional deposits are present in Jadar, Cínovec, Beauvoir, Valdeflores and other areas.

**In a pessimistic scenario**, only conventional Li types may be considered, so that most of **Europe's potential is represented by spodumene-bearing pegmatites in Portugal, Finland, Sweden, Ireland, Austria, Spain and Ukraine**. In an optimistic scenario, that includes an economic mineral processing of micas (zinnwaldite, lepidolite) and jadarite, **Europe's potential is represented by spodumene and/or lepidolite pegmatites, rare-metal granites, greisens and jadarite from Portugal, Finland, Sweden, Ireland, Austria, Spain, France, Czechia, Germany, Serbia and Ukraine**.

**Note: this statement also needs to be counterbalanced by the European potential for lithium-bearing geothermal fluids (also unconventional) that is not investigated in this study, yet possibly significant, at least, in the Upper Rhine Valley at the French/Germany boundary.**

### 4.2 Cobalt

Currently, Finland is the only EU country with primary (mine) production of cobalt. However, in the past, cobalt has been produced in many European countries such as Norway, Germany, France and Slovakia, for example.

Using today's economic parameters, **Scandinavia** and **Finland** have the potential for future cobalt production. The current producing mines in Finland (Kevitsa, Sotkamo) have estimated life-of-mine until the 2030s, with possible further production coming online in the mid to late 2020s, depending on permitting. Other sources could include sulphidic tailings from past, operating, and future mines. Exploration underway in Sweden and Norway could also result in new operating mines with potential Co-production.

The lateritic deposits of the **Balkans** and **Greece** could be a significant source of cobalt, but this would require building new processing plants utilizing HPAL (high-pressure acid leaching) or other hydrometallurgical technologies for cobalt metal or chemicals production.



In most cases, historic cobalt production in central and southern Europe has come from relatively small but high-grade deposits, such as polymetallic vein-type deposits. There has been renewed interest in some parts of Europe for sites such as Dobsina and Kolba deposits in Slovakia, Leogang in Austria, NW Spain and Aquablanca in southern Spain, and the Piedmont area in northern Italy. However, the true economic potential for future cobalt production from any of these deposits is hard to evaluate; they might be suitable for portable and scalable mining and processing, particularly if the price of cobalt increases (e.g., CORDIS 2020).

### 4.3 Graphite

Even if graphite is a common mineral in many metamorphic rocks, localities which can be regarded as of economic interest are not so common and unevenly distributed in Europe. We regard the following areas and countries to have the most significant future potential:

**Scandinavia.** We regard this as the most important graphite regional area. The main production of graphite occurs in Norway, in a province where several hundred million tons of indicated resources are identified, and potential and several new prospects are under development. Similarly, in Finland and Sweden, resources are also in several tens of million tons in several localities.

**The Czech Republic.** This country has been an important graphite producer until recently. Large resources are identified in several places and technology for improved beneficiation is under development. Should the market conditions be favourable, the Czech Republic is likely to continue at the same levels.

**Austria.** Here are a large number of graphite occurrences and likely has future potential. The graphite from Austria is an amorphous type and has a slightly different end-use compared to flake graphite.

**Ukraine.** Ukraine is a large graphite producer and has resources identified in the order of a hundred million tons. In all probability, Ukraine can be an important future producer. However, at the time of writing, the political stability of the country is uncertain.

In summary, graphite resources exist in Europe, and if these are put into production, it is possible to reduce the criticality of this commodity.



## 5. Conclusions

This report describes the aggregation of occurrence data for lithium cobalt and graphite occurrences in Europe from data primarily collected from national mineral resource databases of the project partners.

The main finding of Work Package 5 is that there is no lack of lithium, cobalt and graphite resources in Europe: The necessary geological conditions exist and are very unlikely to limit the future production of energy critical materials. The degree of knowledge relevant to any new exploration of most potential occurrences and metallic provinces are very variable. We must assume that technology related to extraction and processing will develop so that smaller and less rich mineral occurrences will be more attractive in the future. With this in mind, we believe that the potential for future utilisation lithium cobalt and graphite can be summarized as follows:

**Lithium:** The European potential is represented by spodumene and/or lepidolite pegmatites, rare-metal granites, greisens and jadarite from Portugal, Finland, Sweden, Ireland, Austria, Spain, France, Czechia, Germany, Serbia and Ukraine.

**Cobalt:** Scandinavia and Finland, in particular, have a potential for future cobalt production. Further sources could also include sulphidic tailings from past, operating, and future mines. Exploration underway in Sweden and Norway could also result in new operating mines with potential cobalt production. The lateritic deposits of the Balkans and Greece could be a significant source of cobalt, but this would require the development of new more advanced, and increased capacity of hydrometallurgical processing.

**Graphite:** The area we regard with the highest potential is Scandinavia. As an industrial mineral, graphite is much more tailored to specific customers by the producer, than are lithium, cobalt and other metals. However, with a good synergy between producers and customers, a potential for new graphite production also exists in Ukraine, Austria and the Czech Republic.



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## Appendixes

### Appendix 1 List of partners and contributors

|                                           |                                                        |
|-------------------------------------------|--------------------------------------------------------|
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| Sebastian Pfeleiderer                     | Jan Sverre Sandstad                                    |
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| <b>Czech Geological Survey</b>            | Terje Bjerkgård                                        |
| Bohdan Kříbek                             | <b>Portugal</b>                                        |
| Helena Skarková                           | <b>LNEG</b>                                            |
| Jaromír Starý                             | Augusto Filipe                                         |
| Michal Poňavič                            | Carlos Inverno                                         |
| Petr Rambousek                            | Daniel de Oliveira                                     |
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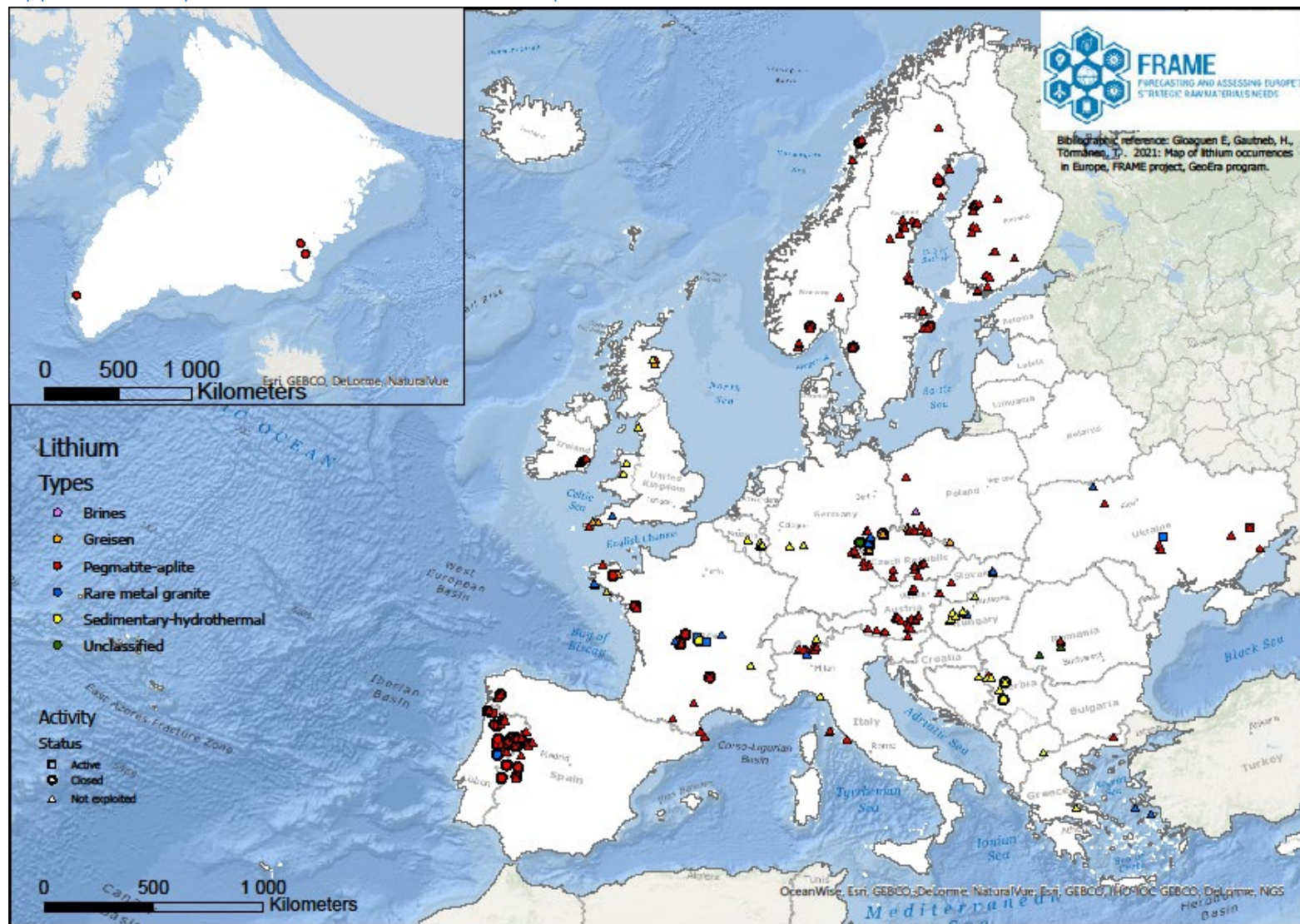




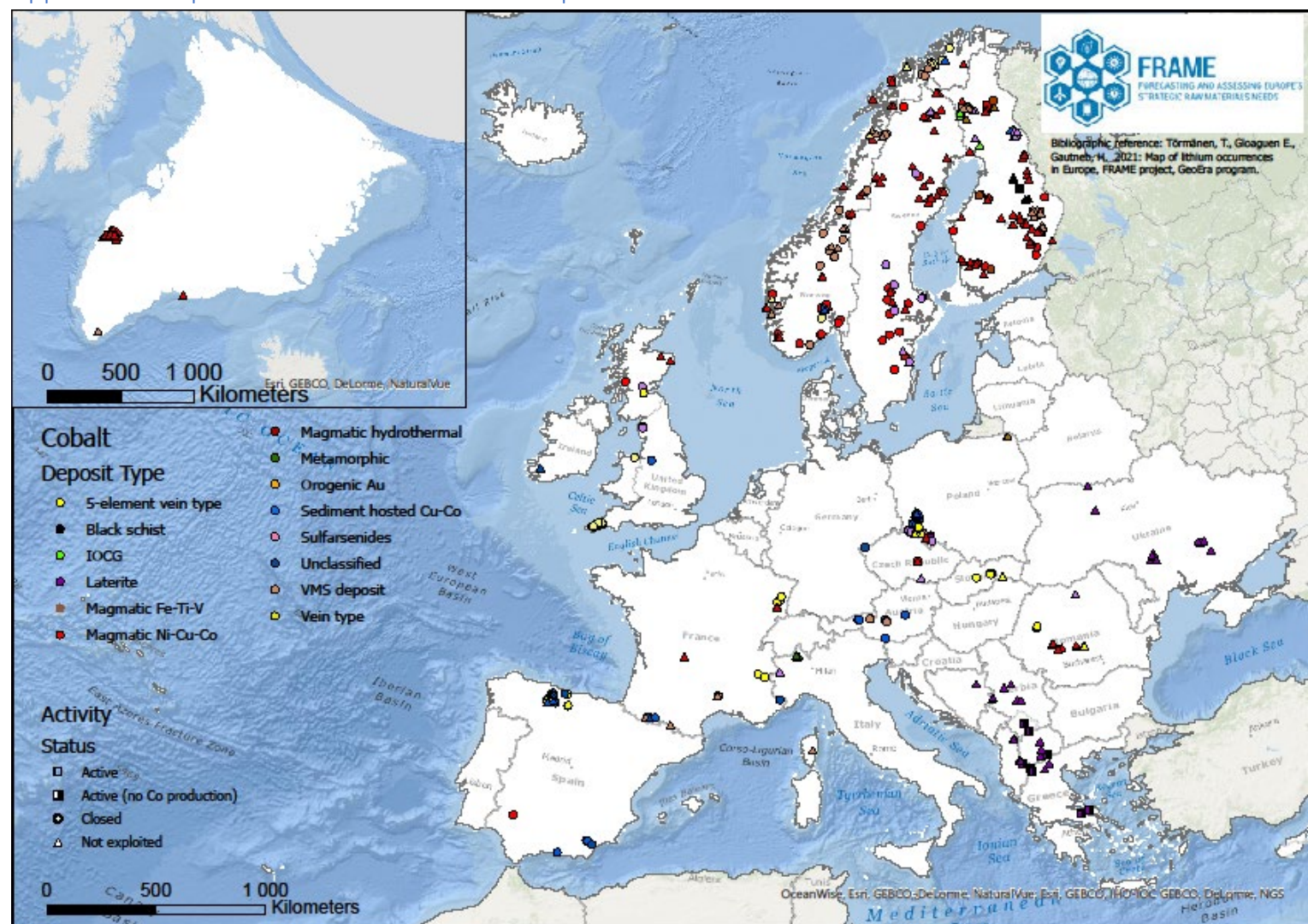
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## Appendix 2 Map of lithium occurrences in Europe.



## Appendix 3 Map of cobalt occurrences in Europe



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## Appendix 4 Map of graphite occurrences in Europe

