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Potential primary CRM supply from EU sources

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Summary

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Approval

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CRITICAL RAW MATERIALS IN EUROPE

GEOLOGICAL PERSPECTIVES ON DOMESTIC EUROPEAN SUPPLY OPTIONS

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In spite of being an "old mining continent", Europe currently imports a significant part of its mineral raw materials supply, especially those commodities that are critical for the European industry in the framework of the energy transition. Still, a major geological potential within the European Union exists and domestic extraction and production of mineral raw materials that are critical for the energy transition, information and communication technologies, and other strategic industrial sectors is a strategic option. In the following pages, we present a synthetic overview of the European onshore potential for critical raw materials using geological understanding of mineral deposit systematics as the technical framework.

1. Introduction

As of 2020, the list of Critical Raw Materials (CRMs) for the EU consists of 30 individual substances (https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en), which, in terms of their material characteristics, can be grouped into 6 categories:

- Chemical elements: antimony (Sb), beryllium (Be), bismuth (Bi), cobalt (Co), gallium (Ga), germanium (Ge), hafnium (Hf), indium (In), lithium (Li), niobium (Nb), phosphorus (P), scandium (Sc), strontium (Sr), tantalum (Ta), titanium (Ti), tungsten (W), vanadium (V)
- Groups of chemical elements: heavy rare earth elements (HREE), light rare earth elements (LREE), platinum group elements (PGE)
- Minerals: barite, borate, fluorspar
- Rock types: coking coal, natural graphite, phosphate rock, bauxite
- Biological product: natural rubber
- Industrial processing products: magnesium metal, silicon metal

For geological or economic considerations, it is important to understand that some of the elements on the CRM list occur as major components in particular minerals, whereas others are minor or trace contributions to the chemical composition of minerals consisting primarily of other chemical elements (Table 1). For example, lithium is the principal cation in silicate minerals such as spodumene ($LiAlSi_2O_6$), whereas indium and germanium dominantly occur as a minor component in sphalerite (zincblende, (Zn,Fe)S) and chalcopyrite ($CuFeS_2$) substituting zinc and copper in the crystal lattice of the host minerals.

Concentrations of rocks and minerals with the potential for eventual economically viable extraction are referred to as "ore deposits". The terms "mineral deposit" and "mineral occurrence" are used for occurrences of geological significance, but where economic parameters are not considered. Investigations in the geological systematics of ore or mineral deposit formation processes are the subject of "mineral deposit studies" or "economic geology".

Table 1. The principal mineral carriers for the elements included in the EU2020 CRM list.

CRM element	Mineral with CRM element as main constituent	Extractable CRM as a minor or trace element substitution
Be	Beryl $Be_3Al_2Si_6O_{18}$	
Bi	Bismuthinite Bi_2S_3	Galena PbS; Tetrahedrite $(Cu,Fe)_{12}Sb_4S_{13}$
Co	Cobaltite CoAsS; Skutterudite $CoAs_3$	Pentlandite $(Fe,Ni)_9S_8$; Pyrite FeS_2; Pyrrhotite FeS; Gersdorffite NiAsS
Ga		Sphalerite (Zn,Fe)S; Gibbsite $Al(OH)_3$; Goethite Fe(OH)O
Ge		Sphalerite (Zn,Fe)S; Chalcopyrite $CuFeS_2$
In		Sphalerite (Zn,Fe)S; Chalcopyrite $CuFeS_2$; Stannite Cu_2FeSnS_4; Tetrahedrite $(Cu,Fe)_{12}Sb_4S_{13}$

Hf		Zircon $ZrSiO_4$; Baddeleyite ZrO_2
Li	Spodumene $LiAlSi_2O_6$); Zinnwaldite $KLiFeAl(AlSi_3)O_{10}(OH,F)_2$; Jadarite $NaLiSiB_3SiO_7(OH)$	
Mg	Magnesite $MgCO_3$; Dolomite $(Ca,Mg)CO_3$; Carnallite $KMgCl_3{\cdot}6(H_2O)$; Polyhalite $K_2Ca_2Mg(SO_4)_4{\cdot}2(H_2O)$; Brucite $Mg(OH)_2$	
Nb	Columbite-Tantalite $(Fe,Mn)(Nb,Ta)O_6$; Pyrochlore $(Na,Ca)_2Nb_2O_6(OH,F)$	Rutile TiO_2
Ta	Columbite-Tantalite $(Fe,Mn)(Nb, Ta)O_6$	Rutile TiO_2
Ti	Ilmenite $FeTiO_3$; Rutile TiO_2	
Sb	Stibnite Sb_2S_3; Tetrahedrite $(Cu,Fe)_{12}Sb_4S_{13}$	
Sc	Thortveitite $Sc_2Si_2O_7$	Clinopyroxenes; Amphiboles; Columbite-Tantalite $(Fe,Mn)(Nb,Ta)O_6$; Ixiolite $(Ta,Nb,Sn,Mn,Fe)_4O_8$; Ilmenite $FeTiO_3$; Baddeleyite ZrO_2; Ferric oxyhydroxides
Sr	Celestite $SrSO_4$; Strontianite $SrCO_3$	
W	Wolframite $(Fe,Mn)WO_4$; Scheelite $CaWO_4$	
V		Magnetite Fe_3O_4; Roscoelite $K(V, Al,Mg)_2AlSi_3O_{10}(OH)_2$; Illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2{\cdot}(H_2O)]$
REE	Bastnäsite $(Ce,La)CO_3F$; Monazite $(Ce,La,Th)PO_4$; Xenotime $(Y,Dy,Er,Tb,Yb)PO_4$	Apatite $Ca_5(PO_4)_3(F,Cl,OH)$; Eudialyte $Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)_3(Cl,OH)_2$; Steenstrupine $Na_{14}REE_6(Mn,Fe)_3(Zr, U, Th)(OH)_2(PO_4)_7$ $Si_{12}O_{36}$ $3H_2O$
PGE	PGE sulphides, arsenides, and sulpharsenides, PGE-Te-Bi-Sb minerals, PGE alloys	Pentlandite $(Fe,Ni)_9S_8$, Pyrrhotite FeS

2. CRMs, mineral deposit types and metallogenetic provinces

Based on our scientific understanding of mineral deposit formation processes, the potential of CRM supply from mining in geologically potential regions can be investigated from geological evolution of the area, rock types, minerals, and contained chemical elements. Such favourability or prospectivity studies integrate mineral deposit research and regional geoscientific knowledge (including all relevant geodata), since certain mineral raw material resources are linked to particular geological characteristics of the Earth's surface and subsurface. For example, gallium can be enriched in bauxite, which is a rock type related to tropical to subtropical weathering (“lateritization”) of granitic rocks. Therefore, regions with granitic rocks that were exposed on the surface during warm and humid time periods of the Tertiary era (66 to 2.6 million years ago) are prospective for both bauxite and gallium resources. However, this example also highlights potential pitfalls, since many bauxite deposits in Mediterranean Europe are in fact hosted by limestone corroded by natural processes ("karstified") and experienced a distinctive line of geological events leading to bauxite formation. Also our understanding of mineralization processes is constantly evolving leading to mineral deposit discoveries in unexpected regions and discovery of deposits of previously unknown types, too. This is underlined by the recent discovery of the large lithium resource at Jadar (western Serbia) hosted by a Tertiary sedimentary-evaporitic succession in an ancient lake environment. Prior to this discovery, the general understanding was that all significant lithium resources in Europe are hosted by particular magmatic rocks (lithium pegmatites).

The fact sheets that accompany the criticality assessment reports provide information regarding the general characteristics of the geological systematics governing the global supply options for each CRM:

- "European Commission, Study on the EU’s list of Critical Raw Materials (2020), Factsheets on Critical Raw Materials" (Latunussa et al., 2020).
- "European Commission, Study on the EU’s list of Critical Raw Materials (2020), Factsheets on Non-critical Raw Materials" (Eynard et al., 2020).

Furthermore, the Critical metals handbook is an important source of reference (Gunn, 2014).

In order to focus such general and global scale considerations to the question of regional prospectivity for CRM endowment in Europe (EU27, United Kingdom, EEA, Western Balkans region, and Greenland), it is important to integrate mineral deposit knowledge, systematics of the CRM mode of occurrence (i.e., individual rock type and CRM component in host mineral(s) with other major chemical constituents) and regional geology.

However, as a first step, the linkages of CRM endowment and mineral deposit types, which in turn are constrained to particular geological formations that define metallogenetic provinces, must be established (Table 2). This concept was also used as a basis for prospectivity analyses in the GeoERA FRAME project (https://www.frame.lneg.pt/).

In general terms, mineral deposits can be categorised into distinct classes according to the major processes responsible for their formation (Table 2). In a concept presented by Arndt et al. (2017), magmatic, magmatic hydrothermal, amagmatic hydrothermal, sedimentary, weathering, and diagenetic to metamorphic deposit classes are distinguished, based on the principal geological processes governing mineral deposit formation. However, these processes must be interpreted from geological evidence, and it is important to note that the scientific understanding is constantly evolving. Hence, the correct interpretation of the observations and analytical data are in many cases not easily agreed upon by geologists. An example of current scientific debate in this regard is the question whether iron oxide–apatite deposits (such as the famous Kiruna iron deposit in northern Sweden) are the result of certain magmatic processes or linked to crustal-scale hydrothermal circulation of specific aqueous fluids. However, for the majority of ore deposit classes, there is general scientific agreement on the general mineral deposit formation processes and of the associated mineral and metal assemblages.

For the purpose of the question under consideration, it is important to highlight the general linkages between mineral deposit types with relevance to the European geology and their (potential) endowment with individual CRMs. This exercise demonstrates that certain groups of CRMs are concentrated in certain mineral deposit types and classes (Table 2). Additional perspectives have been added by considering the relative importance of certain ore deposit types regarding potential CRM endowment. For example, the REE potential in carbonatite and alkaline granitoids is well demonstrated whereas the resource potential of REE in ion-adsorption clay deposits is unknown and possibly minor for Europe and Greenland.

In the following subsections, the characteristics of mineral deposit types in relation to CRM endowment are described with the intention to elaborate on the geological systematics governing CRM primary supply options in Europe. Important sources of reference include Groves and Bierlein (2007), Frenzel et al. (2016a, 2016b), Goldfarb et al. (2016), Arndt et al (2017), Werner et al. (2017). Information on mineral deposits and CRM potential in the Nordic countries (Finland, Greenland, Norway, and Sweden) is based on Weihed et al. (2008), Eilu (2012), Maier et al. (2015), and Eilu et al. (2021), and references therein.

2.1 Mafic to ultramafic magmatism – potential CRM endowment: Co, PGE, Sc, Ti, V

Mafic to ultramafic layered intrusions are the main source of platinum-group metals (PGE) and vanadium (V) globally. Such deposits occur in particular layers (cm- to m-scale thickness) within large (km scale) solidified magma chambers. The formation processes are linked to distinct dynamics in such magmatic systems where important parameters include interaction with the bedrock surrounding these magma masses. Their principal, but not exclusive, geological setting is linked to Precambrian terrains, especially to Archean shields. Hence, the potential for PGE and V supply in Europe is particularly high in northern Finland and parts of Greenland (e.g., Kolb et al., 2015).

In a similar way, there are magnesium-rich lava flows that are restricted to the geological conditions during the early stage of the formation of the Earth's crusts during the Precambrian. Such “komatiites” are potential hosts to Cu-Ni sulphide ores, and Co can be an accompanying commodity (substitution into pentlandite minerals). In addition, there is potential for PGE endowment. Again, most of this mineral potential in Europe occurs in northern Fennoscandia and Greenland.

A related ore deposit type is nickel mineralization in mafic to ultramafic intrusions. Here, Co is commonly present as substitution of Ni in pentlandite, and the PGE are typically present as by-products. This deposit type is exploited at the Kevitsa mine (Finland) representing the main primary source of PGE and Co in Europe currently (Note: Co is also an important resource at the Talvivaara mine in Finland, which is a shale hosted sulphide deposit).

Furthermore, titanium-iron oxides in mafic intrusions are a common source for Ti ± V. Oxides and silicates in mafic intrusions also are a potential source of gallium (Ga) and scandium (Sc) in apparently relatively rare intrusions with unusual compositional characteristics (Wang et al., 2021). Mafic intrusions with substantial Ti deposits are mined in Norway (Tellnes: the only Ti mine in Europe). Of all known European Ti resources, 90 % are in Finland, Greenland, Norway, and Sweden, all hosted in mafic intrusions.

2.2 Evolved Magmatism – potential CRM endowment: Be, Fluorspar, Hf, Li, Nb, P, phosphate rock, REE, Si, Sr, Ta

In general, mafic to ultramafic magmas can be considered as the direct products of melting in the Earth's mantle, whereas processes of magma differentiation lead to particular, evolved magmas with a wide range of compositional characteristics. One such process is immiscibility of distinctive melt phases such as silicate, oxide, and carbonate melts. One model for the formation of the Kiruna iron oxide–apatite (IOA) deposit (north Sweden) invokes such immiscibility of an iron-oxide melt phase and a silicate melt phase leading to the concentration of magnetite bodies. While iron has been produced at Kiruna for over 100 years, the associated apatite is separated from the ore as a waste material and deposited in tailing ponds. The REE content of this apatite is currently a subject of investigation regarding extraction of a marketable REE product, together with phosphate for fertilizer production (https://ree-map.com/). The current understanding of IOA deposits implies that suitable geological conditions are mainly restricted to the Precambrian and, hence, to the Fennoscandian shield and Greenland (Andersson et al., 2021). Possibly related to the Kiruna-type ores are the iron oxide-copper-gold (IOCG) deposits, which in Europe are known to occur, at least, in Finland and Sweden. Regarding the CRMs, the IOCGs have a by-product potential for Bi, Co, P and REE.

Magmatic differentiation processes are also responsible for the formation of large-scale, differentiated peralkaline and carbonatite complexes containing substantial carbonatite and apatite-rich zones. Apatite is mined as source of P (for fertilizer production) in Finland (Siilinjärvi deposit), and similar deposits are known elsewhere in Finland, and from Norway, Sweden and Greenland. Additionally, there is potential for significant Be, REE, Sc, Sr, Nb, Ta, and Hf endowment (occurring as substitution in both silicates, apatite, and other phosphates) in such a setting (e.g., Verplanck et al., 2016; Wang et al., 2021). Carbonatites are also a feature of magmatism in younger continental rift environments such as the Upper Rhine graben (Kaiserstuhl volcanic complex) and the Devonian Kola Peninsula province, which extends to the territory of Finland.

Another distinct type of evolved magmatism leads to the formation of alkaline granitoids, which can be the host to P, REE, Hf, Be, Nb-Ta and fluorspar mineralization. These are the product of magmatic differentiation processes in continental rift of intraplate hotspot tectonic environments (Dostal, 2016). Many areas in Europe with exposed plutonic rocks include domains consisting of alkaline granitic rocks (e.g., Massif Central, Bohemian Massif, Gardar Province); however, they are generally absent in Archean shields, except where there is a relatively young rift across the Archean bedrock (e.g., the Devonian rifting within the Kola Peninsula and adjacent area to the west in northernmost Finland).

An important rock type associated with formations of highly differentiated silicate melts are coarse-grained pegmatites. These may fractionate in a way that REE, Be, Li and/or Nb-Ta containing minerals and very-high purity quartz are concentrated (London, 2016). Pegmatites are commonly associated with evolved granitic plutons and interpreted as late stage, fluid-rich melts segregating into the surrounding country rock. Hence, prospective areas for such mineralization would be defined by occurrences of large granites. However, recent research indicates that some pegmatites may well be associated with melt generated during high-grade regional metamorphism (anatectic melting). This concept opens up a different type of geological terrain to be included in pegmatite prospectivity analyses. Pegmatites with Li, Be, Nb-Ta, and high-purity quartz resource potential are currently known from several parts of Europe, including Finland, Greenland, Norway, Portugal, Spain, France, and Sweden (e.g., Gourcerol et al., 2019).

Table 2. Mineral deposit types and their potential CRM endowment on land within the EU. Dark green: main EU sources of the metal (mined in EU). Light green: major potential sources within EU. Blue: minor potential within EU. White: resource potential within EU unknown but possibly minor.

Class (based on principle geological process governing mineral deposit formation)*	Mineral deposit type*	PGE	V	Ti	Co[1]	Sc[2]	REE[3]	Hf[4]	Nb and Ta[5]	P[6]	phosphate rock	Be	Li[7]	Si	Fluor-spar	Sr	Baryte	W	Sb[8]	In[9]	Ga[9]	Ge[9]	Bi[10]	Mg	Borate	Bauxite	Coking coal	natural graphite
Mafic to ultramafic magmatism	PGE deposits in layered mafic-ultramafic intrusions	X	X[11]		X																							
	Cu-Ni deposits in ultramafic lavas (komatiites)	X			X																							
	Nickel and titanium deposits in mafic-ultramafic intrusions	X	X	X	X	X																						
Evolved magmatism	Iron-oxide apatite deposits[12]						X[12]			X[12]	X[12]																	
	Carbonatites and peralkaline granitoids[13]					X	X	X	X	X[13]	X[13]				X	X												
	(alkaline) granitoid intrusions						X	X	X	X	X	X			X													
	Felsic pegmatites[14]						X		X			X	X	X														
Hydrothermal fluid flow with linkages to magmatism	Granite-related vein deposits (including Greisen)					X			X				X	X	X		X	X										
	IOCG deposits		X[11]		X[22]		X																X					
	Epithermal base metal deposits																X		X	X	X	X	X					
	Skarn																	X		X	X	X	X					
	VMS deposits				X[15]												X		X	X	X	X	X					
Amagmatic hydrothermal fluid flow	SEDEX (clastic-hosted) Pb-Zn deposits																X			X	X	X	X					
	MVT type (carbonate-hosted) Pb-Zn deposits[16]				X										X					X	X	X	X					
	Stratabound clastic-hosted U(-Mo) deposits		X			X	X																					
	Sediment hosted stratiform Cu-Co-Ag deposits (Kupferschiefer)[17]	X[17]			X[17]																							
	Soapstones after ultramafic rocks				X																			X				
	Orogenic Gold deposits				X[18]														X				X					
Sedimentation and near-surface chemical precipitation	Sand deposits			X+			X+	X+	X+					X														
	Phosphorite deposits						X			X	X																	
	Evaporite deposits												X			X								X	X			
	Shale-hosted Ni-Zn-Cu-Co deposits	X	X[19]		X																							
Weathering, diagenesis to metamorphism	Bauxite (aluminium laterite)		X			X							X								X[20]					X		
	Ion-adsorption clay deposits						X				X																	

	Ni Laterite				X	X																						
	Carbonate-replacement deposits																							X				
	Coal																				X[21]	X[21]					X	
	Graphite																											X
	Eclogite-hosted rutile deposits			X																								

*: Modified from Arndt et al. (2017) Only mineral deposit types with relevant potential for CRM endowment and importance to the geology of Europe and Greenland are considered here.
+: Heavy mineral sand deposit are rare in Europe. However, processing of high-purity quartz sand products is associated with removal of the heavy mineral fractions that locally includes ilmenite, magnetite, rutile, anatase, zircon, monazite, gold, and/or Nb-Ta oxides. Ilmenite beach sand deposits in NW Greenland are currently investigated for their economic potential (Dundas ilmentite project)
[1]: As a minor element in Ni-sulfide minerals (pentlandite and others) in magmatic and hydrothermal deposits.
[2]: In amphibole, pyroxene and apatite; e.g., Sc resource of the Kiviniemi deposit (Finland).
[3]: Includes eudialyte, steenstrupine; monazite, apatite, and others.
[4]: In zircon minerals.
[5]: In Nb-Ta oxide minerals.
[6]: In phosphate minerals such as apatite.
[7]: In silicate minerals such as spodumene and zinnwaldite and in lithium-boron mineralization (jadarite mineral) at the Jadar sediment-evaporite deposit in Serbia.
[8]: In stibnite and tetrahedrite.
[9]: As trace element in Zn sulfide mineral sphalerite and Cu sulphide mineral chalcopyrite.
[10]: As trace element in Pb sulfide mineral galena.
[11]: In V-rich iron oxide.
[12]: Also called the Kiruna-type. REE are trace elements in apatite.
[13]: Includes the Sokli alkaline-carbonatite massif and apatite mining at Siilinjärvi carbonatite complex (Finland).
[14]: In particular, this refers to peraluminous rare-metal pegmatites.
[15]: Outokumpu (Finland), Løkken (Norway).
[16]: Including the Irish-type deposits.
[17]: In Europe, this ore deposit type is represented by the Kupferschiefer, currently mined in Poland. The African Copper belt (Zambia, DRC) is the other prime global example. In Europe, the contained PGE is currently recovered whereas the Co is not.
[18]: Orogenic gold with anomalous metal association (Finland).
[19]: Vanadium-bearing mica, e.g., the Talvivaara deposit (Finland)
[20]: As trace element in Al hydroxide minerals of bauxite.
[21]: From Ga- or Ge-rich fly ash processing (coal powered energy generation).
[22]: As a minor element in iron sulphides.

2.3 Hydrothermal fluid flow with linkages to magmatism – potential CRM endowment: V, Co, Sc, Nb-Ta, Li, Si, W, Sb, In, Ga, Ge, Bi, Baryte, Fluorspar

During the late stages of subsurface granitic magma solidification, volatile-rich fluid phases are accumulating and eventually released into the surrounding country rocks along cracks and fissures. Interaction with the surrounding rocks (including previously solidified portions of the emplaced magma body) may occur. Dispersive fluid-rock interaction generates zones of hydrothermal alteration, and a particular result of alteration in this geological setting is referred to as "greisen". In practice, there are various forms of transitional features between pegmatite (implying crystallisation from a fluid-rich melt) and hydrothermal veins (implying crystallization from an aqueous fluid phase). Granite-related vein deposits are a prominent feature of historic mining regions (such as Cornwall, United Kingdom, and Erzgebirge, Germany) and prospective for CRMs such as Nb-Ta, Li, W, Baryte, and fluorspar (London, 2016; Gourcerol et al., 2019).

A similar style of mineralization but formed closer to the surface of continents and volcanic islands, are epithermal base-metal deposits, which commonly are directly linked to volcanism. Formation of baryte and Sb deposits can be associated with this style of hydrothermal activity. Trace elements such In, Ga, Ge and Bi are linked to the occurrence of sphalerite and galena. Such deposits are especially common in the Balkans, in a region extending from Greece to Slovakia.

Limestones and marls of the continental crust can act as effective chemical traps for circulating, metal-bearing magmatic-hydrothermal solutions causing the formation of skarn deposits. The fluid–carbonate interaction processes can result in the formation of W deposits as well as Zn-Pb deposits with potential for Bi, Ga, Ge, and In (substituting into galena and or sphalerite).

Volcanogenic massive sulphide (VMS) deposits are associated with submarine volcanism. Active hydrothermal fields on the seafloor ("black smokers") are regarded as natural laboratories reflecting the processes involved in the formation of these mineral deposits. On the continents, they occur in volcano-sedimentary successions representing marine basins that subsequently were accreted to continents because of convergence and deformation during mountain-building processes. They are characterized by masses of pyrite, pyrrhotite, sphalerite, chalcopyrite, and galena in variable proportions. Varieties rich in sphalerite and galena have potential for Ga, Ge, In, Sb, and Bi endowment since these elements are substituting into the crystal structure of these major sulphides (Monecke et al., 2016). In addition, baryte is a typical gangue mineral of VMS deposits.

Europe has experienced several periods of extensive mountain building (e.g., the Svecofennian, Caledonian, Variscan, and Alpine orogenic phases). Hence, there are numerous areas of known VMS mineralization along previous tectonic collision zones (e.g., Skellefte Field in northern Sweden; Iberian Pyrite Belt in Spain and Portugal; Troodos Massif in Cyprus; Røros district in Norway; Parys Mountains in the United Kingdom). A somewhat atypical but significant VMS district is Outokumpu (Finland) because here cobalt-rich iron sulphides and pentlandite are an important part of the massive sulphide ore bodies (Peltonen et al., 2008).

2.4 Amagmatic hydrothermal fluid flow – potential CRM endowment: V, Ti, Co, Sb, Ga, Ge, In, Bi, PGE, Baryte, Fluorspar

Hydrothermal fluid flow in sedimentary successions relates to distinct mineral deposit formation processes. Current understanding indicates that limestone-hosted Pb-Zn deposits (also referred to as Mississippi Valley Type; MVT) are the result of saline pore waters circulating in the continental crust that lose their capacity to transport metal ions when they encounter carbonate rock acting as a chemical trap. Initiation of this fluid movement may be linked to increasing lateral pressure during the initial stages of plate convergence. Also, the mixing of ascending, reduced fluids and descending, oxidized fluids (groundwater), as well as migrating hydrocarbons can contribute to the trapping mechanism and mineral deposit formation. In terms of CRM endowment, Bi, Co, Ga, Ge, and In may be present as trace elements substituting into sphalerite and/or galena (Marsh et al., 2016). In addition, fluorspar is a common mineral of MVT deposits. In Europe, major metallogenetic provinces of this type are the Eastern Alps, Cracow–Silesian area (Poland), and the Midlands Basin (Ireland).

The Pb-Zn deposits hosted by clastic sediments (sand- and siltstones) are traditionally referred to as SEDEX ("sedimentary-exhalative") deposits. They consist of cm-scale layers of sulphides with intercalations of (fine-grained) siliceous sediment. A currently forming SEDEX deposit is located at the bottom of the Red Sea, known by the name "Atlantis Deep". Here, the importance of saline fluids is clearly demonstrated by the extensive, metal-rich brine pools on the sea floor. The saline fluids are inferred to be sourced from subsided evaporate units formed during initial stages of opening of the rifted basins. Fluid circulation may be driven by thermal gradients due to subsidence and/or by magmatic intrusions into the deeper portions of the rifted continental crust. Similar to limestone-hosted Pb-Zn deposits, the principal potential endowment of CRMs includes Ga, Ge, and In substituting into the sphalerite and Bi substituting in the galena crystal structure (Marsh et al., 2016). Furthermore, baryte is a common mineral in SEDEX deposits. Major examples of SEDEX deposits in Europe are Rammelsberg and Meggen (Germany), formed in conjunction with extensional plate dynamics during the Variscan orogeny.

Uranium deposits in sandstones are an important deposit type, and the Wismuth mine, exploited in Eastern Germany, is a prominent example in Europe. In addition to U oxides, the hydrothermal regime is suitable for the formation of minerals containing significant REE, Sc and V, constituting potential by-products in uranium deposits (Breit, 2016).

A metallogenetic province of global significance is the Permian "Kupferschiefer" extending from eastern Germany to southern Poland. The Kupferschiefer is a major source of Cu and Ag in the mining district of Silesia (Poland). Recent investigations have shown that there is a potential of by-product Co in these deposits (e.g., Pietrzela, 2022). There is also a minor palladium and platinum production from some of the Kupferschiefer deposits (Marsh et al., 2016).

The formation of talc, serpentine and magnesite is a typical result of low-temperature fluid-rock interaction in ultramafic magmatic rocks under metamorphic conditions in early stages of mountain building. The resulting rock type is commonly called 'soapstone'. During this process, Mg is mobilized due to the breakdown of silicate minerals and precipitated as $MgCO_3$ (magnesite), if CO_2-rich fluids are involved. In the alteration process, cobalt and nickel may be mobilized from silicates into sulphides and become by-products of talc and magnesite mining, as is the case for the talc mines in Finland.

Orogenic gold deposits can be described as gold-bearing quartz-vein occurrences generated during mountain-building processes. They are inferred to form as a result of focused flow of water–CO_2 fluids of deep crustal origin. While the main commodity of economic interest is of course gold, there are several areas of both gold and antimony associations in Europe (e.g., Seinäjoki area, Finland, Kreuzeck-Goldeck Complex in Austria, and Armorican Massif in France). In northern Finland, there are at least two belts of the gold–cobalt subtype of the orogenic gold category (Kuusamo and Peräpohja belts; Eilu, 2015).

2.5 Sedimentation and near-surface chemical precipitation – potential CRM endowment: Ti, REE, Nb-Ta, Li, Ga, Sr, Mg, V, Co, P, phosphate rock, borate

Erosion and transportation by streams and rivers are effective mechanisms to concentrate minerals that are resistant to mechanical and chemical attack. Hence, so called "heavy minerals" such as rutile, ilmenite, zircon, and monazite are common target commodities of mineral sand mining. Globally, these deposits are the largest source of primary titanium. Whereas the potential for such deposits is highest in the tropics (due to suitable weathering conditions), there is a limited potential in Europe. On the other hand, there is abundant sand mining in Europe where quartz of variable purity is the main target. In such operations, the associated heavy mineral fraction is removed during the processing stages. Hence, the quartz-sand mining has a by-product potential of Ti, Hf, REE and Nb-Ta. It is important to note that ilmenite ($FeTiO_3$) beach sand deposits are known from western Greenland and are currently investigated for their economic potential (Dundas ilmenite project; Bluejay mining (https://bluejaymining.com/projects/greenland/dundas-ilmenite-project/).

Stable continental shelf and platform environments above 500 m water depth, at low paleolatitudes, are suitable for sedimentary phosphate rock (phosphorite) deposits (Emsbo et al., 2016). In Europe, substantial phosphate deposits formed during the Cambrian to Ordovician (539–444 million years ago) and occur in Belgium (Stavelot-Venn Massif) and northern Estonia (Vind, 2018). These deposits represent CRM endowment for phosphate rock, P, and the REE (as substitution in apatite).

Mineral precipitation due to evaporation can result in the formation of various salts, sulphates, and borates. In particular, the formation of celestine ($SrSO_4$) in such environments represents an important source of Sr. Major Sr deposits occur in southern Spain where almost all strontium mining in Europe and nearly half of the global production takes place. It should be noted that replacement processes during diagenesis may play a crucial role to form this type of mineralization. In a related sedimentary setting, borates are linked to volcanic-hydrothermal activity in arid environments. The recent discovery of a very large lithium–borate resource (1.16 Mt lithium, 6.65 Mt boron) at Jadar, western Serbia, is an example of such type of mineral deposit (Gourcerol et al., 2019). The discovered ore mineral was named "jadarite" ($NaLi[B_3SiO_7(OH)]$).

Evaporate sequences also include very large Mg resources in the form of potassic magnesium salts, dominantly carnallite ($KMgCl_3 \cdot 6(H_2O)$), kainite ($KMg(SO_4)Cl \cdot 3H_2O$), magnesite ($MgCO_3$), and dolomite ($(Ca,Mg)CO_3$). Furthermore, the world's largest known polyhalite ($K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$) resource is in northern England. This deposit is known as the Woodsmith Mine project and currently under development by Anglo American plc. Some evaporitic magnesite deposits are also known from Serbia. Also note that many of the magnesium salts are important sources of potassium, an element that may become a CRM in near future due to its importance for fertilizer production and the fact that nearly 40 % of the current (2021 data) mine production is from Russia and Belarus.

A quite distinctive depositional environment is represented by Ni-Zn-Cu-Co deposits in black shales, such as the Paleoproterozoic Talvivaara deposit (Terrafame mine) in Finland. The "low grade–high tonnage" characteristic of this style of mineralization requires application of heap leaching metal extraction processes, and Co is a by-product of the Ni extraction circuit. The current resource of Talvivaara contains 300,000 t Co (including 100,000 t Co in reserves), i.e., it is by far the largest Co resource in Europe. At Talvivaara, there are also indications of a major vanadium and minor PGE endowment that would require further investigation. Potential for additional discoveries of black shale hosted base metal and CRM ores is restricted to Paleoproterozoic sedimentary successions of Fennoscandia, and to Palaeozoic black shales of Sweden and Estonia. The latter have much lower metal grades and the ore units are thinner than at Talvivaara, but they represent a potentially very large Ni and V resource. For example, it is estimated that the Estonian black shales together could contain about 50 million tons of vanadium (Vind, 2018).

2.6 Weathering, diagenesis to metamorphism - potential CRM endowment: Bauxite, Co, Sc, REE, Ga, Mg, Ge, Ti, coking coal, natural graphite, phosphate rock

Compositional changes to the original rock formations can be related to numerous geological processes including weathering, diagenesis, and metamorphism. For instance, intense *in-situ* chemical weathering under tropical climate causes the formation of laterite. For granitic rocks, lateritization can lead to substantial enrichment of aluminium hydroxides referred to as bauxite. In Europe, tropical conditions during the Tertiary were responsible for bauxite formation. The origin of limestone-hosted bauxite deposits, common in Mediterranean Europe, has been the subject of scientific discussions. Fluvial transportation of silicate-material during phases of submergence into karstified limestone areas is currently the commonly agreed mineral deposit formation model.

The main commodity extracted from bauxite is aluminium. However, during the leaching process involved in the processing of the bauxite an insoluble residue is generated referred to as "red mud" that consists mainly of quartz, calcite, hematite, and goethite (hence the red colour). Depending on the composition of the primary rock type and the conditions of the weathering processes, certain trace elements may be concentrated, including Sc, V, Ga, Li and P. Most notable is the elevated concentration of Ga in some red mud processing residue tailing ponds in Europe representing a potential secondary CRM resource.

A particular type of weathering related mineralization is the formation of "ion adsorption clay deposits" that are known for HREE endowment and can be extracted by *in-situ* or heap-leaching processes (Sanematsu and Watanabe 2016). Mining of such deposits is common in China and Myanmar. In Europe, weathered parts of some carbonatites and alkaline granitoids settings are reported to exhibit similar (paleo) weathering zones with a HREE and phosphate potential.

The formation of nickel laterite occurs under similar conditions as the formation of bauxite deposits. The difference comes from the rock types subjected to weathering, being mafic to ultramafic in composition. In Europe, these are rocks from sections of oceanic lithosphere that were accreted to the European continent during plate collision and mountain building. Important deposits of Ni laterites are common in the western Balkans and in Greece. Similar to the sulphidic deposits associated with mafic to ultramafic magmatism, there also is potential for Co and Sc endowment in Ni laterites.

Magnesite ($MgCO_3$) is mainly mined as an industrial mineral for processing into refractory materials but has also been a common starting point for Mg metal production. The magnesite is either an evaporate, a result of soapstone formation, as described above, or a replacement product of dolomite (calcium-magnesium carbonate) formed in marine environments (e.g., Hochfilzen deposit, Austria). It is unclear whether the replacement of dolomite occurs during (late) stages of diagenesis or during independent replacement processes associated with mobilization of Mg-rich formation waters that may be linked to distant processes of collisional tectonic plate movements.

Despite efforts to decrease the usage of coal in general, in order to limit the release of CO_2 to the atmosphere, it is noteworthy that coking coal is included in the list of critical mineral raw materials. This is unrelated to the usage of coal for heating or electricity generation but linked to the requirement of using high-quality coal as a reductant in the dominant steel-making processes. Hence, this type of coal is also referred to as “metallurgical coal”. Coal of such high quality was the main product of underground mining in the Ruhr area of western Germany (Carboniferous coal seams). Mining was discontinued due to high costs of deep (>1000 m) mining; however, the resource potential remains in the Ruhr region. Some coal-fired power plants generate Ge- and/or Ga-rich fly ash, which can be recovered. This particular stream of Ga and Ge supply can be expected to play a diminishing role on the pathway to a “zero-emission” energy industry.

Graphite is a form of solid carbon, in very thin sheets with a hexagonal symmetry that typically is a product of metamorphic recrystallization of carbon-rich sediments. Generally, larger crystals (so-called “flake graphite”) is the product of relatively high metamorphic conditions deep in the Earth's crust (>600 °C; 3–7 kbar). This form of graphite is desired by the modern electronics industries, especially as anode material in Li-ion batteries. Prospective regions for flake graphite are high-metamorphic-grade terranes with rock successions of sedimentary origin, black shales turned into schist and gneiss. Such areas are present in the numerous orogenic belts developed in Europe during the Svecofennian, Caledonian, Variscan and Alpine mountain-building phases. Very little graphite is currently mined in Europe, 90 % of this in Norway, despite a significant general endowment.

A particular type of titanium oxide (rutile) mineralization is associated with metamorphic rocks, formed under high pressure and temperature conditions, referred to as eclogite. Under such conditions, iron-titanium oxides of mafic rocks are replaced by rutile (TiO_2). Prominent examples of this type of mineralization in Europe are present in Norway (e.g., at Engebøfjellet).

3. Assessing the European geological potential for CRM endowment using metallogenetic maps and mineral prospectivity/favourability maps: examples of successful recent pan-European collaboration

Most of the mineral raw materials critical for the EU are extracted and produced outside Europe. Consequently, the European Union largely depends on imports to satisfy the needs of its manufacturing industries. However, this situation must not be mistaken for a lack of geological endowment in Europe. Rather, it is a consequence of a complex interplay of global trade competition, political decision making, reduced funding for geological research and exploration, and the general negative perception of the mineral industry by the society and many NGOs.

From the geological perspective we can highlight regions of known potential for CRM endowment based on our current understanding of mineral deposit formation models and the various regional geological characteristics in Europe. Cleary, this is constantly evolving in relation to the amount of effort invested in a certain research areas. For example, the investigation of lithium deposits in recent years has opened up paleo-lake deposits (e.g. Jadar, Serbia) and anatectic pegmatite deposits (e.g. Koralpe, Austria) as newly identified geological environments for lithium endowment.

Overall, there is a geological potential in Europe that could supply the European industry for a significant part of its needs. Due to their long and complex geological history, European terrains provided favourable conditions for the formation of a variety of mineral deposits in time and space. Distribution of metallogenic provinces strongly correlates with geological domains and their geodynamic and tectonic evolution. To provide a schematic overview of the European continent, the largest metallogenic provinces are shown in Figure 1. They include the Fennoscandian Shield, Caledonian province, Variscan province, Alpine province, and the Gardar and North Atlantic igneous provinces in Greenland comprising (Sadeghi et al., 2020).

In order to facilitate the development of exploration projects and, ultimately, mining in Europe, several EU-funded projects focused their efforts on building digital knowledge infrastructures (e.g., ProMine that ended in 2013, EGDI-Scope that ended in 2014, Minerals4EU that ended in 2016, and GeoERA-Mintel4EU that ended in 2021). These projects developed pan-European databases on mineral resources and tools to query and diffuse them. They provided critical inputs to build a harmonized and exhaustive INSPIRE-compliant knowledge on European mineral resources. This knowledge is nowadays publicly accessible on the EGDI (European Geological Data Infrastructure) online platform (https://www.europe-geology.eu/). Based on this geological and metallogenic knowledge, several EU-funded projects identified the most important areas in Europe in terms of mineral resources exploration and extraction. This work was done following different approaches, amongst which the two mains are i) the mapping of metallogenic provinces, and ii) mineral prospectivity mapping (MPM).

The mapping of metallogenic provinces consists of defining areas that contain deposits and/or occurrences of a targeted commodity (recognized by exploration works) that bear similar characteristics in a homogeneous geological context that is favourable for the occurrence of such mineralization. This approach is essentially based on expert knowledge on the distribution of deposits and their genetic processes. In the GeoERA-FRAME project that ended in 2021, Sadeghi et al. (2020) produced metallogenic maps of Europe for several critical raw materials (lithium, cobalt, natural graphite, phosphates, niobium, tantalum, and REE). These maps, in their digital version, can be displayed and downloaded from the EGDI online platform (https://www.europe-geology.eu/map-viewer/; go to "mineral resources" and "metallogenic areas" in the left-hand side "Layers" menu).

Thanks to the progress of computing capacities during the last decades, and the development of European mineral resources databases, it is possible to process data with different GIS and statistical approaches to deliver maps showing favourable areas referring to a specific commodity. Carranza (2017) describes mineral prospectivity mapping (also called Mineral Potential Modelling, MPM) as "quantifying and mapping of the likelihood that mineral deposits may be found by exploration in a study area". The basic purpose of prospectivity mapping is to assess the spatial distribution of the favourability of occurrence of a non-random phenomenon (assuming that a phenomenon cannot be predicted if it is purely random). In the case of mineral prospectivity mapping, the phenomenon is the occurrence of mineralised bodies. A large number of mineral prospectivity mapping methods exist. They can be grouped in two categories:

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

The ProMine project (2009–2013) produced the first pan-European database of mineral deposits and – based on it – the first prospectivity maps for critical raw materials at European scale (Cassard et al., 2015). Despite being partly outdated, several of these maps (for cobalt, tantalum, antimony and tungsten) are available on the EGDI platform (https://www.europe-geology.eu/mineral-resources/mineral-resources-map/critical-raw-materials-map/; go to "critical raw materials occurrences" and "predictive map" in the left-hand side "EGDI – Mineral resources" menu). These prospectivity maps are based on two data-driven approaches: 1) the Weight of Evidence method (Bonham-Carter et al., 1988, 1989; Agterberg et al., 1990), and 2) the DataBase Querying method (DBQ; Bertrand et al., 2017; Gourcerol et al., 2022). The DBQ method was specifically developed to assess favourability of minor – or by-product – commodities in the parageneses, where they were seldom searched for in the past. Overall, the ProMine project made an important step forward in terms of both mineral resources databases and mineral prospectivity mapping at European scale.

In addition to the metallogenic maps from Sadeghi et al. (2020), the GeoERA-FRAME project also produced mineral prospectivity maps for lithium, cobalt, natural graphite, phosphates, niobium, tantalum and rare earth elements (Bertrand et al., 2021). These maps are based on a mineral prospectivity method called CBA (Cell-Based Association; Tourlière et al., 2015) that was specifically developed to avoid biases linked to uncertainties in polygon contours (e.g., lithology polygons) and point locations (e.g., deposits) that could be significant at continental scale, and to consider the geological context in the vicinity of deposits. As for the ones from the ProMine project, these mineral prospectivity maps are available on the EGDI platform, in the FRAME project-dedicated map viewer (https://data.geus.dk/egdi/?mapname=egdi_geoera_frame#baslay=baseMapGEUS&extent=416820,968810,719081

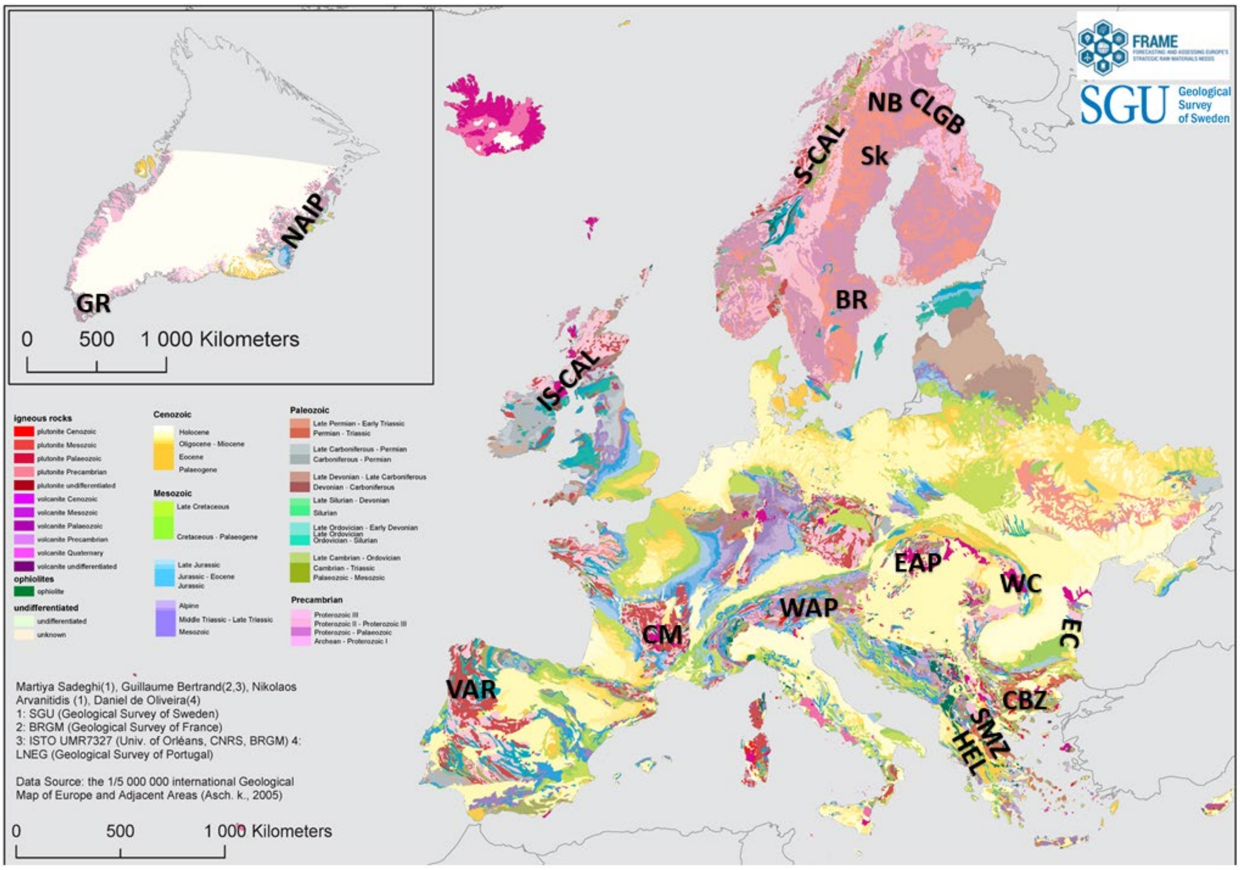

Figure 1. Overview of the main metallogenetic areas in Europe on the geological map of Europe and Greenland, (modified after Asch, 2005; in Sadeghi et al., 2020). GLGB: Central Lapland greenstone belt; NB: Norrbotten; Sk: Skellefte; BR: Bergslagen; S-CAL: Scandinavian Caledonides; IS-CAL: Ireland-Scotland Caledonides; EAP: Eastern Alpine province; WAP: Western Alpine province; WC: Western Carpathian; EC: Eastern Carpathian; CB: Carpathian-Balkan Zone; SMZ: Serbian-Macedonian Zone.

0,4642020&layers=egdi_eurare_occurrences&filter_0=commoditieslist_hidden.part%3D%26significance%3D; go to "Critical Raw Materials" in the left-hand side menu, and click on the data layers named "[commodity name] CBA favourability map of Europe").

Ultimately, the goal of these metallogenic and mineral prospectivity maps is to provide impartial and objective information on favourable areas in Europe for mineral exploration. At European scale, this information highlights areas of high mineral potential that deserve more detailed assessments to further investigate and, possibly, quantify mineralization potential. As such, it is a valuable input for further and more detailed studies by exploration companies and national geological surveys.

4. The way forward

Investigation of prospectivity and favourability based on expert knowledge of mineralization processes is a complex endeavour and best carried out individually for each type of mineral deposit. The methodology was pioneered by the US Geological Survey and institutions with considerable experience in this line of application of mineral deposit geology research, which in Europe are GTK (Geological Survey of Finland) and GEUS (Geological Survey of Denmark and Greenland). We can safely assume that similar evaluations have also been done in China, Russia, and some other countries, but the results of the work has been kept confidential.

For practical reasons, such studies are conducted within particular jurisdictions providing the framing conditions of the exercise. However, national borders are rarely a natural limit to geological parameters. Hence, it would be a significant step forward in the investigation of potential CRM endowment in Europe if investigations would be organized with the scope to define prospectivity zones in individual metallogenetic provinces based on the pooled data and knowledge from the respective geological institutions involved in the area.

From a geological perspective, it is important to stress the underlying interrelations of commodity endowment that are outlined in Table 2 and explained in section 2 of this report. Certain commodities are linked together by nature depending on the mineral deposit formation process. Also, some CRMs occur in a restricted number of deposit types (e.g., bauxite) whereas others occur in a number of different geological environments (e.g., Co). It is also paramount to stress that mineral deposits of one particular CRM is a rare exception, examples being bauxite and graphite. Commonly, the CRMs occur together with "non-CRM" commodities, typically as substitution in the crystal lattice of primary ore minerals such as pentlandite, galena, sphalerite, or chalcopyrite.

From an exploration point of view, the approach to look at supply options for each CRM individually has its limits. Rather, it makes more sense to work on the basis of mineral deposit types and include "non-CRMs" in the considerations for further investigations. Such a pioneering prospectivity mapping work has been done by Gourcerol et al. (2022) in the frame of the ION4RAW project. Hence, it would be beneficial to extend the current map collection for metallogenetic areas in the EDGI viewer with maps outlining the areas containing the mineral deposit types and classes as described in section 2 and summarized in Table 2.

Prospectivity mapping is an evolving science and is strongly dependent on the quality of input data and research regarding the mineral deposit formation processes. As such, it is an important tool that can help to find more deposits of known general characteristics. New discoveries in unexpected settings, such as the Jadar lithium deposit (Western Serbia) in paleo-lake deposits, add new perspectives that highlight the need for continuous update and improvement of such tools.

In order to move forward with mineral deposit science and exploration, it is important to join expert groups across Europe from academia, government, and the minerals industry. This would be best achieved in working groups tackling particular mineral deposit types. For example, investigation on carbonate-hosted Pb-Zn mineralization (potential CRM endowment: Co, In, Ga, Ge, Bi and fluorspar) would combine institutions from Ireland, Poland, Denmark, and the Eastern Alps (Italy, Austria, Slovenia) and appropriate industry partners. This would ensure that scientific work is carried out in a holistic mineral systems approach based on the best available knowledge in order to define exploration parameters that might outline areas with mineralization potential. Whereas it is commonly agreed that indications for near-surface deposits in Central Europe have probably been found in historic times, much of the subsurface (10 to 500 m depth) is poorly explored. Also, the trace element endowment is poorly documented and significant resources may be present in historic mine waste dumps.

In addition to technical exploration work, where geologists can have the most significant input, it is important to bear in mind that many exploration and mining projects are facing strong opposition in society. Communication between researchers, minerals industry, and stakeholders should be strengthened in order to improve the understanding of benefits and risks associated with the development of mineral resources in mining operations. In some way, fact-based discussions need to be encouraged. In this context, transdisciplinary research including colleagues from social and political sciences should be encouraged.

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