ProMine Mineral Databases: New Tools to Assess Primary and Secondary Mineral Resources in Europe

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Abstract

A major objective of the ProMine project was to develop a Pan-EU GIS data management and visualization system for natural and man-made mineral endowment and the implementation of a Pan-EU predictive resource assessment, and thus to provide a renewed picture of European metallogeny. To reach this objective, ProMine work package 1 produced pan-European databases of primary and secondary mineral resources, the ProMine Mineral Deposit (MD) and Anthropogenic Concentration (AC) databases. The present version of the MD database contains 12,979 records (mines, deposits, occurrences or showings) and covers 34 European countries. The total number of records of the AC database is 3408. As an exhaustive inventory of mineral wastes in Europe was far beyond the scope of the project, ProMine focused on major anthropogenic concentrations (i.e. mining and ore processing wastes) and on the most interesting in terms of volume/tonnage and content (e.g. possible presence of critical metals). After briefly presenting the databases—their structure, the way they were fed and their content—the present chapter focuses on how they can allow (i) geological approaches such as the spatial and temporal distributions of commodities and/or deposit types (and, in turn, the identification of metallogenic epochs), as well as (ii) statistics calculation on the main commodities and metallogenic types present in Europe and their contribution to the EU mineral budget. In addition, it is shown that the thorough and homogeneous data contained in the MD database also allows calculation of mineral potential and predictive maps

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at European scale. Given the limited number of parameters—present in an homogeneous way—which can be used when working at continental scale, different methods of calculation have been adapted: for the calculation of potential, kernel density and weighting have been used, and for predictivity mapping, besides the use of the well-known Weight-of-Evidence (based on lithostratigraphy) for main commodities present in an ore deposit, a new method using metals associations has been set up for by-product commodities in formerly known deposits. Working at European scale, one should however keep in mind that such studies cannot be used for targeting. The aim is more realistically to precise or to redefine 'district' contours and in the best case to enhance 'some less obvious' areas. In order to display and to deliver data through the Internet, a web portal was developed. The ProMine web portal architecture is based, especially for metadata and web services, on OGC [Open Geospatial Consortium (http://www.opengeospatial.org/)] principles related to open architecture and interoperability. A mapping between the data stored in the ProMine databases and standard data models like GeoSciML for geological information and EarthResourceML for mineral deposits, mines and mining wastes has been implemented to deliver the data according to these international standards.

2.1 Introduction

ProMine was a European Union (EU) co-funded project, of which the main objective was to stimulate the extractive industry to deliver new products to the manufacturing industry. The purpose of the geological parts of the project was to deliver interactive GIS tools and 3D and 4D models of deposits and mineralized belts. These would in turn contribute to define new reserves of minerals—with a special focus on strategic ones—in the European Union, so that the extractive industries can quantify and exploit in the future, and which could be the source of raw materials for the manufacturing industries. The main objectives of developing the GIS tool were: (i) to develop a geographic information system of primary and secondary mineral resources covering all European countries, (ii) to produce derived predictive resource assessments, and (iii) to deliver this data through an on-line data management and visualization system. The purpose of this was to provide a new picture of European metallogeny, replacing the most recent continental synthesis that was published by UNESCO (1984) over 20 years ago.

Three main targets were identified, implementing the latest developments in metallogeny and database management:

- Evaluation of EU mineral resources, including new strategic and 'green'[1] (Hocquard and Deschamps 2008) commodities such as, for instance, Co, Ga, Ge, In, Nb, Ta, PGE and REE
- Evaluation of secondary (industrial) minerals and resources in combination with metalliferous ores
- Evaluation of potentially valuable mining and metallurgical residues

These data acquisition activities and their dedicated databases allowed a homogeneous multi-layer information system to be developed and delivered. This covered the whole European territory and included not only the mineral

[1]High-tech metals are engaged in the major theme sets of "climatic change", at the level of "renewable energies" and reducing emission of "greenhouse gases". The CO_2 battle is involving a growing number of these "minor" (often by-products) metals which, in this case, can be qualified as ecological "green metals".

deposit and mining wastes layers, but also geological, structural and geophysical layers. The work on developing the GIS tool benefited from work already undertaken by BRGM, like the 'Geology' layer at 1:1,500,000 scale and the 'Mineral deposit' database which served as a basis for the project, reusing parts of the database architecture, the hierarchical lexicons, and records already entered for different BRGM projects such as 'GIS Central and South-eastern Europe' (Cassard et al. 2004), 'GIS Mines France' (Cassard and Lambert 2007), 'GIS Karelia' (Tkachev et al. 2008) and various regional syntheses.

The completion of the inventory, i.e. entering all missing deposits in a consistent way, ensuring that the level of knowledge and of representation is similar throughout Europe, and that the mineral endowment of belts on which WP2 focused was particularly well described—was mainly undertaken by the national geological surveys involved in ProMine. The GIS so built provides a well-founded representation of EU's mineral potential and allows the development of a predictive approach to EU's mineral resources endowment. This was accomplished by combining the various thematic layers and by studying their spatial relationships using statistical and geostatistical methods under expert supervision.

However, working at a continental scale presents certain important constraints. The pan-EU 1:1,500,000 scale geological map used results from a process of generalization and homogenization applied to a set of digital country maps generally edited at a larger scale (1:500,000 to 1:1,000,000 scale). The accuracy of such a digital document (e.g. faults and geological formation boundaries representation and location) cannot be perfect and may cause substantial errors in derived maps of mineral potential. In the same way, due to the great number of mineral deposits taken into account, some descriptions are incomplete and some important parameters may be missing. Consequently the calculation of mineral potential derived from them and presented here should be considered as indicative.

The aim of this chapter is not to revisit European metallogeny in detail, instead our intention is to show, through selected examples, that the pan-EU MD database when properly queried, can answer to several types of questions related to mineral resources, notably their quantity, their spatial and temporal distribution, and the location of new exploration targets (Cassard et al. 2012; Gaál et al. 2012, Arvanitidis et al. 2012).

2.2 The Mineral Deposit (MD) Database

2.2.1 Overview of the MD Database Structure

The MD database stores all the information related to mineral deposits in Europe. Each deposit is described in about 40 fields distributed in 8 folders (Table 2.1): (1) General information, including status, owner, location; (2) Deposit information, including deposit type and morphology; (3) Information on mineralization and host rocks, including age of mineralization and host rock, mineralogy of the ore, gangue and hydrothermal alteration, host rock formation name and lithology; (4) Economic information, including the exploitation type, and, per commodity, ore type, former production, reserves, and resources with associated grades; automatic calculation of the potential,[2] per commodity; (5) High-tech metals with, per commodity, the characterization of high-tech metals hosts (mineralogy, grade, abundance) and link with the Anthropogenic Concentration (AC) database; (6) Comments (free text); (7) Iconography, including photographs, sketch maps, cross-sections, etc. and (8) Bibliography, i.e. main geological and economic references related to the deposit.

Most fields that contain text values (i.e. non numerical) are lexicon guided, in order to improve the efficiency of future data processing. Lexicons are either simple (list of values), dynamic (list to which new values can be added) or hierarchical (tree-like list with father/son

[2]Tonnage of commodity (metric tons of metal) in the ore body, based on its grade and the tonnage of ore.

Table 2.1 Organization of the ProMine Mineral Deposit (MD) database (to be exploited by different data queries and extractions)

1. General Information

Lexicon guided fields
- Status: detailed information on mine, deposit, occurrence, showing
- Country: link to list of countries

Free text fields
- Mining company (owner); Mining District
- Longitude (xx.xxx° and xx°xx′xx″), Latitude (xx.xxx° and xx°xx′xx″) (WGS 84)
- Ore deposit name(s): multi-entry field to list all possible names of the same deposit
- Free comment field
- Author + date of entry, Controller + date of control
- Links to other databases and numbering in these databases
- URL + source of the mine site (if any)

2. Deposit information

Lexicon guided fields
- Deposit type(s): multi-entry field of deposit type hierarchical listing
- Main morphology and Deposit morphologies: multi-entry field of deposit morphology hierarchical listing

Free text fields
- Azimuth, dip, length, width, down dip information associated with ore morphology

3. Information on mineralization + host rocks

Lexicon guided fields
- Mineralization stratigraphic age (upper and lower limit)
- Ore mineralogy, Gangue mineralogy, Hydrothermal alteration: multi-entry fields
- Host rock lithologies: multi-entry field and Host rock stratigraphic age (upper and lower limit)

Free text fields
- Mineralization absolute age, Host rock absolute age (with error + dating method from lexicon)
- Host rock formation name

4. Economic information

Lexicon guided fields
- Exploitation type(s): multi-entry field
- Main commodity
- Multi-commodity window: per commodity:
  - ore type; production and grade units
  - former production, grade of former production, duration of former production
  - reserve, type of reserve (proven, probable, measured, …), grade of reserve, year of estimate, classification code used
  - resource, type of resource (proven, probable, measured, …), grade of resource, year of estimate, classification code used
  - automatic calculation of i) former production, ii) reserves, iii) resources and iv) deposit size class

5. High-Tech Metals

Lexicon guided fields

Per commodity
- Characterization of high-tech metals hosts (mineralogy, grade, abundance)

Possibility to create a link with the Anthropogenic Concentration (AC) database

6. Comments
- General comments on geology, General comments on economy, Mine site infrastructure

7. Iconography
- Illustrations (photographies, schemas, cross-sections, etc.) related to the deposit

8. Bibliography
- Geological reference(s), Economic reference(s)

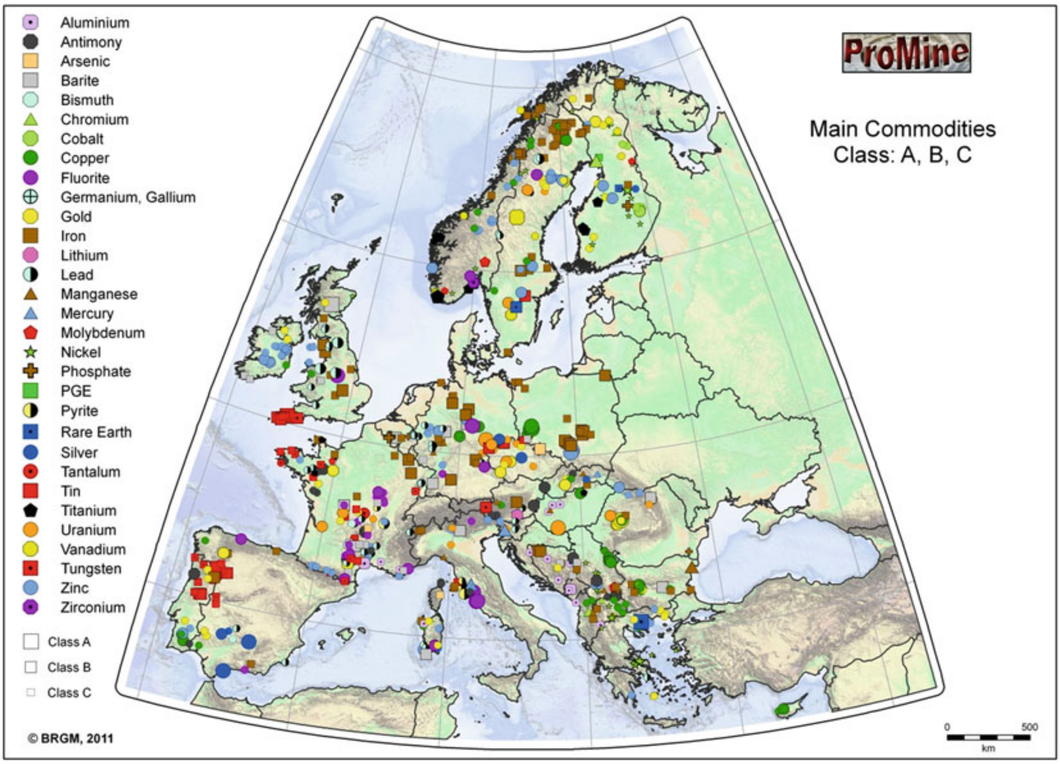

Fig. 2.1 Main deposits of the ProMine MD database, coded for their size (class A–C) and main contained commodity

relationships allowing storage of information according to its level of accuracy).

2.2.2 Overview of the MD Database Content

The total number of records in the MD database is 12,979. Records are either showings, occurrences or mineral and ore deposits. The geographic distribution of records is, to a certain degree, heterogeneous as it reflects the availability and quality of knowledge of primary resources within EU member states. Figure 2.1 shows the spatial distribution of deposits contained in the ProMine MD database, coded according to the main commodity they contain.

Table 2.2 presents elementary statistics on the MD database. Although the aim of the ProMine databases was to compile information as thoroughly as possible, some fields for some deposits have been left blank for several reasons (e.g. no information available, highly doubtful information or classified information). As a consequence, the present study is not exhaustive and the numbers of cumulated tonnages (or 'European endowment') given in Table 2.2 should be considered as rough estimates rather than as precise values. As economic information is not always available, and assuming that all encoding errors that could generate overestimations have been properly eliminated, the calculated endowment figures provided should be regarded as lower end estimations. Nevertheless, aggregated tonnages for the EU are provided in Table 2.2 for 37 important commodities (lead and zinc were grouped and considered as a single commodity). These tonnages are compared to the estimated world mine production (IndexMundi[3]

[3]IndexMundi is a platform containing various data concerning selected attributes and characteristics of countries, including detailed statistics on commodities compiled from multiple sources (http://www.indexmundi.com/en/commodities/minerals/).

Table 2.2 Statistics on the main commodities in EU and their tonnage (endowment: resources + reserves + past production)

Type	Commodity	Criticality (EU list)	Class A No. of deposits	Class A Σ Tonnage	Class B No. of deposits	Class B Σ Tonnage	Class C No. of deposits	Class C Σ Tonnage	Class D No. of deposits	Class D Σ Tonnage	Σ Tonnage (classes A to D)	World mine production, in tons of commodity (2010, Index Mundi estimate)	Equivalent number of years of world production
Precious metals	Ag		5	185,444.4	17	72,933.7	44	42,102.5	94	21,581.1	322,061.7	23,100	13.9
	Au		1	700.2	17	2,826.2	86	2,563.7	164	628.8	6,718.9	2,560	2.6
	PGMs	yes			1	523.6			2	5.7	529.3	466	1.1
Base metals	Al				2	2.94E+08	13	5.45E+08	18	81,156,000	9.2E+08	41,200,000	22.3
	Cu		3	55,826,080	26	65,278,601	68	21,181,016	219	7,591,200	1.5E+08	16,000,000	9.4
	PbZn		3	51,290,000	63	120,717,118	297	64,552,035	425	12,979,515	249,538,668	16,140,000	15.5
	Sn		2	3,266,000	14	1,405,268	22	112,764	18	6,554.6	4,790,587	265,000	18.1
Iron and ferro-alloy metals	Co	yes			3	504,4	34	342,744.4	52	35,811.2	882,955.6	89,500	9.9
	Cr		1	39,500,000	5	46,530,000	4	11,051,694	7	3,233,300	1,00E+08	23,700,000	4.2
	Fe		2	2.42E+09	28	7.96E+09	101	3.1E+09	198	6.76E+08	1.42E+10	1,280,000,000	11.1
	Mn		1	1.16E+08	1	10,750,000	14	53,206,990	31	8,391,079	1.89E+08	14,200,000	13.3
	Mo				5	843,148.6	11	223,339	9	23,117	1,089,605	242,000	4.5
	Nb				1	750	1	25,2	1	3,496	778,696	62,900	12.4
	Ni	yes	3	9,115,000	4	2,823,900	36	3,699,562	61	489,138.5	16,127,601	1,620,000	10.0
	V		1	2,005,733	3	984,252.8	16	767,224.8	19	182,321.5	3,939,532	61,200	64.4
	W	yes			4	374,438.4	21	260,367	21	38,315.2	673,120.6	68,800	9.8
Speciality and rare metals	Be	yes			1	6,664	2	2,257	2	158.5	9,079.5	5,080	1.8
	Bi				2	6,115	2	900			7,015	16,000	0.4
	Cd		1	13,6	2	5,22	6	7,938	5	1,534	28,292	22,800	1.2
	Ga	yes			1	90	1	30	1	3	123	260	0.5
	Ge	yes	1	800	1	174	2	58	3	39	1,071	N/A	N/A
	Hf		1	28,628.9							28,628.9	N/A	N/A
	Hg		2	216			7	15,061	3	551.5	231,612.5	2,250	102.9
	In	yes	2	5,387			1	50	2	15.5	5,452.5	659	8.3
	Li		1	1,280,000	1	215	2	116	4	67,012.8	1,678,013	23,500	71.4
	Rb		1	19,5					1	1.8	19,501.8	N/A	N/A
	Re						1	60	1	43	103	47.,2	2.2
	REE	yes	1	5,675,013	1	446,85	2	110,426	1	8,447	6,240,736	123,000	50.7
	Sb	yes			8	366,341	36	271,177.4	11	13,163	650,681.4	167,000	3.9
	Se						1	433.4	1	52.5	485.9	1,980	0.2
	Ta	yes			2	39,25	1	1,95	3	790.3	41,990.3	682	61.6
	Ti		1	73,440,000	18	1.27E+08	15	11,116,382	9	743,855	2.12E+08	2,210,000	95.9
	Zr		1	1,588,800	5	1,503,200			2	11,381	3,103,381	1,250,000	2.5
Minerals for chemical use	Brt		4	49,362,400	17	37,159,000	32	14,652,350	20	1,971,813	1.03E+08	7,850,000	13.1
	Fl	yes	6	52,621,000	10	20,061,620	21	9,722,000	29	3,330,705	85,735,325	7,180,000	11.9
	Mg	yes	1	2.1E+08	2	39,215,439	10	29,072,080	10	3,593,800	2.82E+08	755,000	373.5
Speciality and other industrial rocks and	Graphite	yes	1	12,300,000	2	2,677,500	6	1,493,200	5	181,88	16,652,580	925,000	18.0

Classes A, B, C and D refer to the ProMine MD database 'REFERENCE_SUBSTANCE' lexicon (see Appendix 1)

estimates for year 2010) and converted to the equivalent number of years of world production. These estimates of total available tonnages clearly identify important endowments for some commodities within the EU. For example, the endowments of vanadium, mercury, lithium, rare earth elements, tantalum, titanium and magnesium are equivalent to 64.4, 102.9, 71.4, 50.7, 61.6, 95.9 and 373.5 years of world mine production at current levels, respectively. Among these commodities, several (rare earth elements, tantalum and magnesium) belong to the list of 14 critical mineral raw materials for EU published by the European Commission (2010, 2011) following the Raw Material Initiative (European Parliament 2008). Other commodities which are also economically important for the European Union have significant endowments that amount to a decade or more of the world mine production (e.g. cobalt, nickel, tungsten, indium, fluorite and graphite). In addition to these estimates, the ProMine project published a preliminary map of the distribution of the 14 critical raw materials, as defined by the European Commission 2010. This was updated after completion of the project (Fig. 2.2). This map represents a significant advance in improving our knowledge of the mineral resources in the European Union.

2.2.3 Stratigraphic Distribution of Mineral Occurrences

The MD database stores information on the ages—both stratigraphic and radiometric—of ores and their host rocks. 3750 records contain information on the age of mineralization. To study the temporal distribution of deposits, records have been sorted into 16 stratigraphic divisions (periods for Phanerozoic and eras for Precambrian). 2445 deposits were unambiguously assigned to a unique selected stratigraphic division, with the remainder being too poorly documented to be accurately categorised. For example, records were not used where the mineralization age was given as Cenozoic,

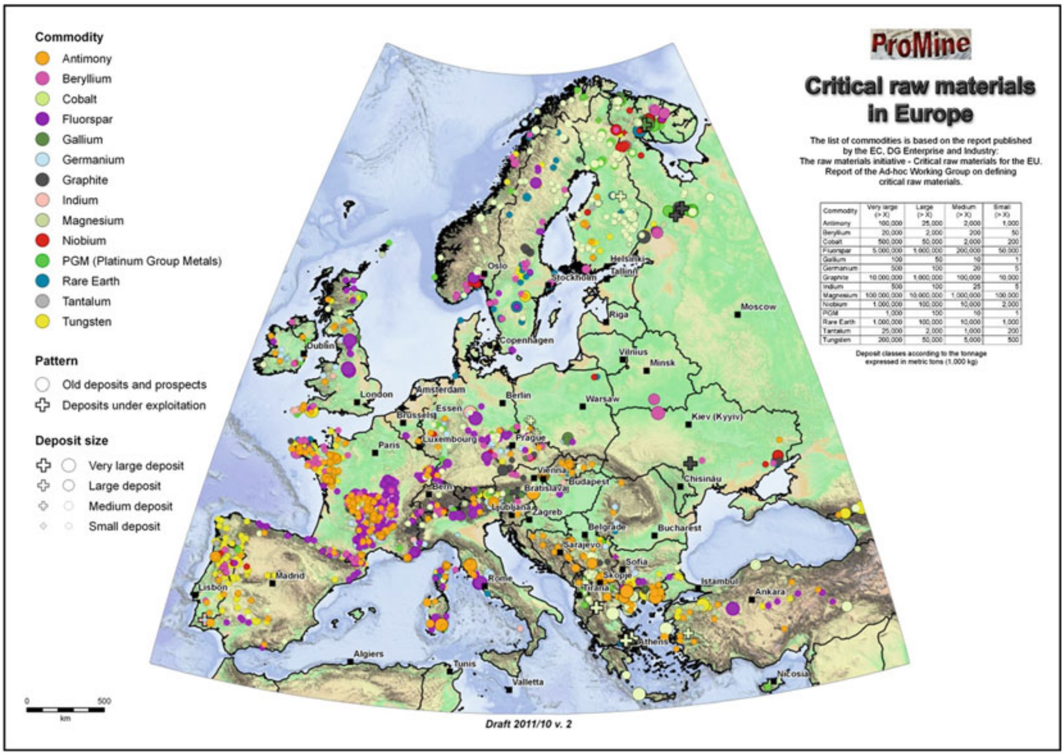

Fig. 2.2 Map of critical raw materials in Europe based on the ProMine MD database and the list of 14 critical commodities identified by the European Commission

Mesozoic, Palaeozoic or Precambrian. This dataset was then sorted by commodity or deposit type to assess the various mineralizing periods that occurred in Europe. As an example, Fig. 2.3 shows the temporal distribution (age of mineralization) of the deposits containing a selection of 6 commodities (aluminum, gold, copper, fluorite, nickel and zinc).

Aluminum is exclusively related to Mesozoic and Cenozoic bauxite mineralizing processes, and particularly to Cretaceous bauxites in southern Europe (Petrascheck 1989) such as the Durancian isthmus in southern France. Mineralizing processes of similar age are also found in lateritic nickel deposits related to the alteration of nickel-bearing silicates in ultramafic ophiolitic formations.

Gold mineralization occurred during several periods of the geological history of Europe. The Neoarchaean is marked by orogenic-type gold-bearing mineralization related to greenstone belts of the Ilomantsi region in eastern Finland (Vaasjoki et al. 1993). They are however of limited importance (Eilu et al. 2012) compared to major gold districts in Australia or Canada (Goldfarb et al. 2001).

The main frequency peak is related to the Palaeoproterozoic of the Fennoscandian Shield, and more precisely to the upper part of Palaeoproterozoic, from 1.9 to 1.8 Ga (Svecokarelian orogeny). This period is marked by polyphase convergence including subduction, island arc magmatism, oblique subduction, basin closure, arc and micro-continent collision and accretion of different terranes. Gold mineralization can be associated with early systems mostly of VMS, porphyry and epithermal types, or with the younger orogenic type (Weihed et al. 2008; Eilu and Weihed 2005).

The Lower Palaeozoic is marked by a peak centred on the Ordovician, which essentially corresponds to gold-bearing VMS in the

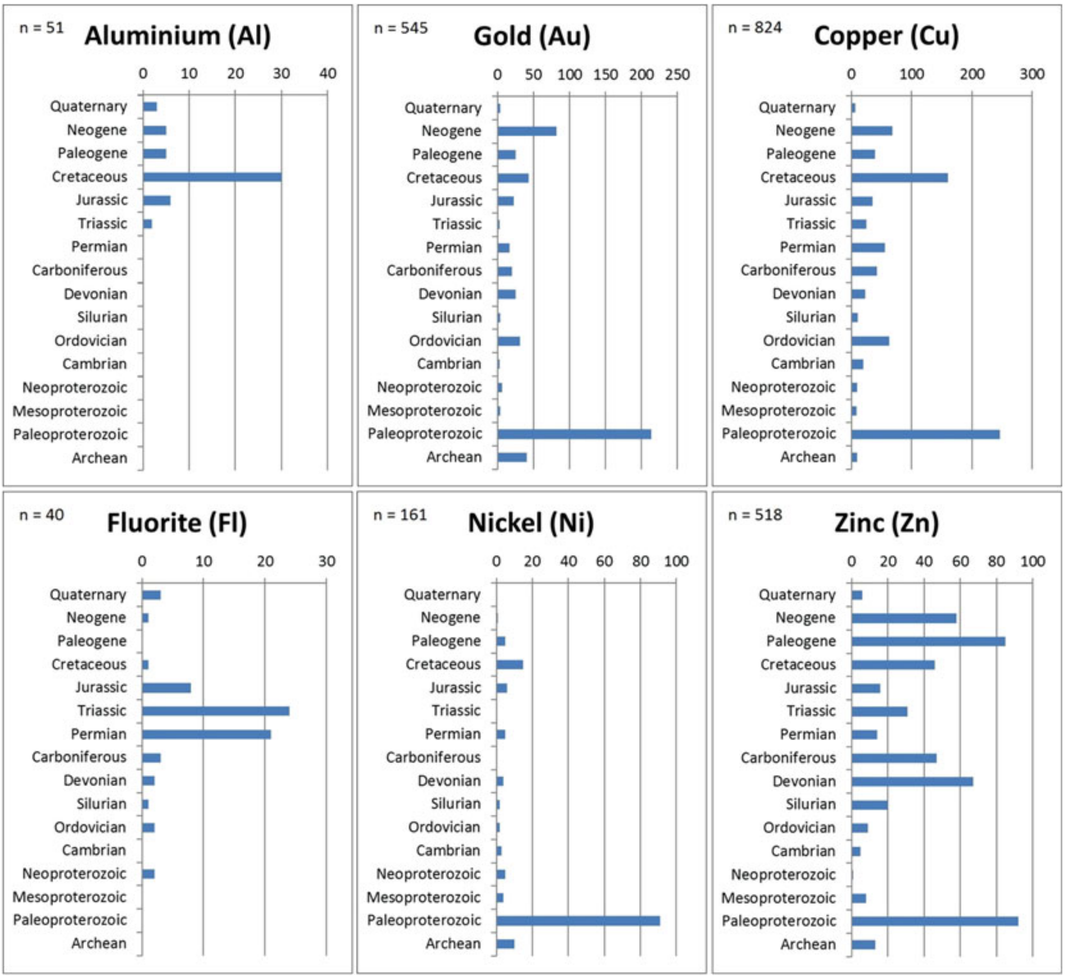

Fig. 2.3 Temporal distribution of selected commodities (n is the number of deposits containing the commodity), per stratigraphic period/era

Caledonian domain of Scandinavia. They are also associated with a more widespread mineralization event in Great Britain and Portugal.

The Upper Palaeozoic is the main gold mineralizing period in the Hercynian. A first episode (Upper Devonian and early Lower Carboniferous) is related to massive sulphides of, for instance, the southern Iberian province (Spain and Portugal) or the Châteaulin basin (France). The second episode is of orogenic type (Bouchot et al. 2005), in relation to the late evolution of the Hercynian orogen (Late Carboniferous and Early Permian).

Younger gold peaks are related to the evolution of Southern Europe along the Tethyan margin in the Balkan-Carpathian domain. Two main periods can be identified: the first one, of Upper Cretaceous age, corresponds to porphyry-type mineralization (Cu and Au), and the second one, of Cenozoic age with a Miocene maximum, is essentially related to epithermal type mineralization.

The temporal distribution of Copper mineralization shows some similarities with that of gold. Three major periods can be identified, with different types of deposits and geodynamic context.

The Fennoscandian domain is characterized by both mineralization related to mafic or ultramafic complexes (Cu, Ni, PGEs), formed mainly during the Lower Palaeoproterozoic (Weihed et al. 2005), and later mineralization related to the Svecokarelian orogeny (Upper Palaeoproterozoic), with mostly volcanogenic massive sulphides (e.g. Outokumpu, Skellefte district; Weihed and Eilu 2005), porphyry and/or IOCG type deposits (e.g. Aitik). The Ordovician of the Caledonian domain in Scandinavia is marked by copper mineralization that formed early with respect to the collision period (Grenne et al. 1999).

The Upper Palaeozoic is an important period for copper mineralization with several episodes associated with various types of deposits. In the Devonian and lowermost Carboniferous, large massive sulphide bodies are emplaced in the southern Iberian province (Leistel et al. 1998). Some of these are very rich in copper, such as Neves Corvo in Portugal. The Carboniferous is associated with numerous copper-bearing polymetallic veins but their economic potential is limited. On the other hand, the Permian hosts the world class Kupferschiefer mineralization in southern Poland and Germany (Hitzman et al. 2010).

The Cretaceous peak is related to both the copper-bearing massive sulphides in Cyprus, and the Cu- and Au-bearing porphyry-type mineralization of the Balkan-Carpathian domain (Jankovic 1997; Lips et al. 2004). In the Tertiary, especially in the Miocene, important Au- and Cu-bearing epithermal mineralization is developed in the Balkan-Carpathian region (Heinrich and Neubauer 2002).

Fluorine mineralisation is commonly associated with barite. It is associated with a main episode related to the evolution of post-Hercynian basin domains in the Triassic (and Permo-Triassic) periods, and the evolution of the European southern margin in the Jurassic (e.g. Lias of the Cevennes border in France). An additional recent episode is related to the Plio-Quaternary volcanism in Latium (Rome region in Italy).

Less important fluorine stratabound mineralization also exists in the Neoproterozoic of Scandinavia and the Cambro-Ordovician of the Pyrenees (France). Numerous Late Hercynian veins (Upper Carboniferous and Permian) also host fluorine.

Nickel mineralisation in Europe occurred during two main periods: (i) the Palaeoproterozoic with nickel sulphide mineralization associated with copper, cobalt and occasionally platinum-group elements, and (ii) the uppermost Mesozoic (Upper Cretaceous and beginning of Tertiary) with nickel-bearing laterite mineralization resulting from the alteration of olivine in ophiolites during intense tropical weathering processes.

Economic nickel sulphide mineralisation (with subordinate Cu and PGEs) is almost exclusively located in the Fennoscandian Shield that is a province of major importance for this type of mineralization. The Neoarchaean komatiites in greenstones belts host some Ni–Cu sulphides deposits of minor importance (e.g. Vaara, Finland).

After the Archaean magmatic and tectono-metamorphic evolution, Fennoscandia underwent a long period of rifting (Weihed et al. 2005). During the Early Palaeoproterozoic (Siderian and Rhyacian) several phases of rifting occurred, probably related to magmatic plume activity, with which several deposits are associated. These include: (i) the Kemi mafic-ultramafic layered complex (Finland) formed during the Siderian, (ii) the Kevitsa deposit (Finland) formed during the Rhyacian, and (iii) the Vammala deposit formed during the Orosirian Svecofennian orogeny. At the beginning of the Palaeozoic, rifting of the Norwegian Caledonian domain was accompanied by the emplacement of mafic-ultramafic complexes associated with Cu–Ni mineralization of minor importance.

The Agua Blanca deposit in Spain formed during the Lower Carboniferous ($\sim$340 Ma; Romeo et al. 2006), at an early stage of Hercynian orogeny. It is one of the few Ni–Cu sulphide deposits related to mafic-ultramafic formations outside the Fennoscandian domain (Martínez et al. 2005).

Zinc mineralization also shows a complex temporal distribution with, essentially, (i) massive sulphides and SEDEX (Sedimentary Exhalative) in the Palaeoproterozoic, (ii) MVT along the margins of southern European basins in the Palaeoproterozoic, and (iii) replacement deposits along the border of porphyry and epithermal deposits of the Balkan-Carpathian domain in Tertiary formations.

The Palaeoproterozoic of Fennoscandia hosts VMS deposits of Rhyacian to Orosirian age (Weihed and Eilu 2005), such as those in the districts of Skellefte (Sweden), Vihanti-Pyhäsalmi (Finland) and Bergslagen (Sweden). The transition between the Upper Devonian and the Lower Carboniferous is a major period for the formation of zinc deposits, essentially the VMS deposits of the Southern Iberian Province (and to a lesser degree in the Châteaulin basin and Brévenne series in France), the SEDEX of the Pyrenees and the SEDEX deposits and carbonate-hosted deposits of Ireland. Late Hercynian veins are marked by the frequent occurrence of zinc, but are of limited importance. Triassic and Jurassic formations hold Mississippi Valley type “carbonate-hosted” deposits emplaced along the margin of Mesozoic basins and forming sub-continuous alignments from north-western Spain through the Cévénole border (France) and the Alpine margin to the Balkan. In the Balkan-Carpathian domain Upper Cretaceous to the Neogene recurrent zinc mineralisation appears as a secondary commodity in porphyry and epithermal deposits. Zinc is dominant in the skarn-type deposits at the boundary between carbonate and high temperature magmatic and hydrothermal intrusions (e.g. Trepča, Miocene age).

2.3 The Anthropogenic Concentration (AC) Database

2.3.1 Overview of the AC Database Structure

The ProMine AC database stores all the information on anthropogenic concentrations related to the mining and metallurgical industries such as mine wastes and unprocessed products (e.g. run-of-mine ore, unprocessed ore stockpiles, mine waste dumps, barren overburden), ore processing wastes (e.g. cobbing wastes, wash tailings, flotation tailings, leach residues, magnetic-separation tailings) and treatment wastes (e.g. smelter wastes, flue dusts, roasting residues, chemical treatment wastes, leach tailings, ashes, cocking plant residues, etc.) Each site is described in about 35 fields distributed in 6 folders (Table 2.3): (1) General information, including status, owner, location and the list of processes that have been implemented on the site; from this folder a link with the MD database can be created, allowing identification of the deposit (s) that fed the site; (2) Information on wastes and products including the type of storage, the type of waste, the mineralogy, estimation of volume/tonnage, the type of commodity available and the grade, with automatic calculation of the potential[4] per commodity, at site scale and the type of environmental impact; (3) The environmental aspects, with per environmental impact, the type of environmental pathways and receptors, the type of water treatment and the description of the type of restoration used. The other three folders—Comments, Iconography and Bibliography—are identical to those of the MD database.

2.3.2 Overview of the AC Database Content

The total number of records of the AC database is 3408. Their spatial distribution and content of critical commodities, according to the list of 14 critical raw material established by the European Commission (2010), is presented in Fig. 2.4. There is a significant variability in the number of records from different countries in the AC database. Some countries like Spain, and to a lesser extent France, are over-represented. This is probably due to the fact that these two countries have already (at least partly) synthesized information related to their wastes for national programmes or completed international projects (e.g. the 5th EU-FP project DECHMINUE—Thomassin et al. 2001).

[4]Tonnage of commodity (metric tons of metal) in the anthropogenic concentration, based on its grade and the tonnage of waste.

Table 2.3 Organization of the ProMine Anthropogenic Concentration (AC) database (to be exploited by different data queries and extractions)

1. General Information

Lexicon guided fields

- Status: information on mining site or plant (mill, smelter, active, inactive, …)
- Country: link to list of countries
- Implemented processing(s): information on ore processing

Free text fields

- Owner(s)
- District/province
- Longitude (xx.xxx° and xx°xx′xx″), Latitude (xx.xxx° and xx°xx′xx″) (WGS 84)
- Mining site /plant name(s): multi-entry field to list all possible names of the same mining site /plant
- Author + date of entry, Controller + date of control
- URL + source of the mine site /plant (if any)
- Links to other databases and numbering in these databases

Possibility to create a link with the MD database: 'Comes from' deposit(s): Name(s) of deposit(s) related to ore processed. Note that the site record has to be created first, and then entered in the Mineral Deposit (MD) database

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2. Wastes and products

Lexicon guided fields

- Multi-storage/waste window: per type of storage and type of waste:
  - – Waste or product storage: type of storage used for wastes or products
  - – Type of waste or product: description of wastes and products; hierarchical listing
    - Mineralogy: waste or product mineralogy
    - Class: category class information on waste or product
    - Commodity(ies): type of commodity(ies) available in wastes or products
      - Unit: unit of commodity grade
      - Manual calculation of estimated resource per commodity
  - Impacts: type of environmental impacts with area affected by pollution and volume of water affected (linked to

3. Environmental aspects)

Free text fields

- Surface area (m^2), volume (m^3), and tonnage (t) of a type of waste or product
- Density retained for calculation
- Grades (min, max, average), date, accuracy of estimation (%)
- Area affected by pollution (km^2)
- Volume of water affected (m^3)
- Comments on impacts (free text)
- Automatic calculation of potential resource, per commodity, at the site scale (synthesis)

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3. Environmental aspects (new window with impact recapitulation—linked under 2. Waste and products/Impacts)

Lexicon guided fields

- Per environmental impact:
  - – Pathways: type of environmental pathways
  - – Receptors: type of environmental receptors
  - – Water treatment: management and treatment processes and structures of water
  - – Restoration: description of restoration used

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4. Comments

- General comments on environmental issues, plant infrastructure (free text)

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5. Iconography

- Illustrations (photographies, schemas, maps, etc.) related to the site

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6. Bibliography

- Reference(s)

Similarly, the completeness of the data is highly variable between countries. This can be accounted for by a lack of information, restricted access to information and by the availability of information dealing only with specific aspects. Examination of the content of the AC database indicates that the

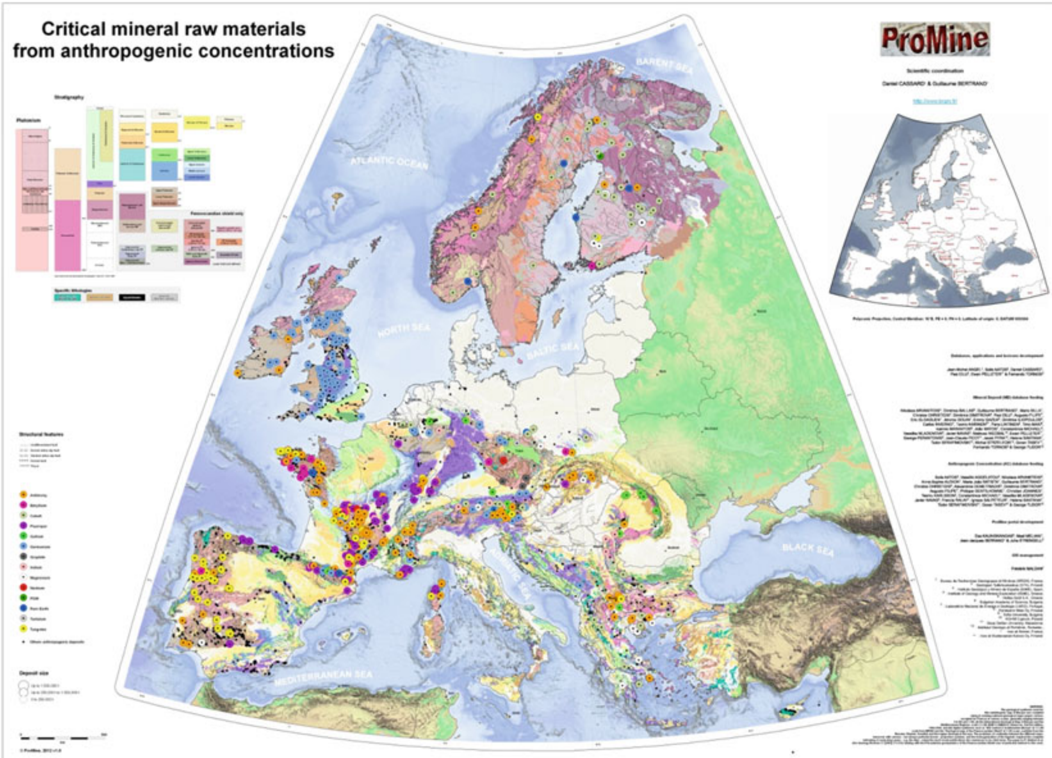


Fig. 2.4 ProMine AC database: spatial distribution of anthropogenic sites with a special attention to sites containing critical mineral raw materials

assessment of anthropogenic concentrations is not a simple task. Nevertheless, compared to the results of previous projects (e.g. DECHMINUE), ProMine has made a significant advance in terms of the number and quality of the records compiled, and has laid the foundation of an infrastructure which is INSPIRE compliant (cf. Sect. 2.6 "Data dissemination and web portal") and which can be used in future projects related to mining wastes.

The ProMine project focused on the largest anthropogenic concentrations and on those of greatest interest in terms of volume/tonnage and content (i.e. possible presence of critical commodities). The aim was to have an inventory, as complete as possible, of concentrations which could be processed for the recovery of strategic/high-tech/critical commodities, and to avoid overlap between the ProMine project and the work done by the member states under the Mining Wastes Directive. The ProMine approach targeted those sites with the greatest potential for the recovery of strategic commodities, with particular emphasis on establishing links with the primary concentration(s). It was beyond the scope of ProMine to compile a comprehensive inventory of wastes throughout Europe. Such a very detailed and systematic inventory was done by Member States in the frame of the Mining Wastes Directives (notably, the directives 2006/12/EC and 2008/98/EC, European Parliament 2006, 2008). This inventory, though, was more focused on environmental impact than on the characterization of secondary resources and, as such, does not overlap with the work done in ProMine.

The definition of the size of wastes (surface occupied, volume or tonnage) and the grade of the contained commodities was a common problem. In many cases, it was impossible to fill

Table 2.4 Statistics on critical mineral raw materials from anthropogenic concentrations

Commodity	Total no. of sites	Number of sites with calculated potential	∑ potential (t)
Be	36	9	41
Co	131	62	39.656
Ga	59	28	8.82
Ge	157	18	408
In	36	7	4.273
Mg	42	27	17,147,091
Nb	18	8	379
Pt	5	1	0.6
REE	13	5	13.755
Sb	198	37	78.299
W	124	23	15.137

these fields in the AC database because of the lack of data. As a result the information collected in the ProMine AC database is essentially qualitative, rather than quantitative, and does not permit the calculation of aggregated resource potential or its spatial distribution. On the other hand, the inventory compiled for the Mining Wastes directive brought useful data on volume and tonnage of wastes in European countries. Although the schedules of the MWD activities and of ProMine did not allow complete integration of the available data, an important future development would be to merge the information from both sources in order to improve the overall quality of the data on secondary resources in Europe.

Despite the data shortcomings, the aggregated potential from a limited number of sites for critical commodities has been calculated and is presented in Table 2.4. It is important to stress that these values are indicative and provide minimum estimates of the potential tonnages available in selected European wastes. It should be noted that these estimates are much lower than those calculated as potentially available from primary resources derived from the MD database (Table 2.2).

2.4 Mineral Potential Mapping

The goal of this section is to identify areas of high mineral resource potential, solely based on the distribution and size of known mineralization, and using spatial extension of 'carrier' (and thus favourable) lithologies. In the present work, potential is understood as being the endowment, i.e. the sum of cumulated past production, reserves and resources.

2.4.1 Methodology

Potential maps presented here show the spatial density of known deposits, sorted by metallogenic families and weighted on their size. 16 deposit 'families' or groups were identified by the ProMine consortium and extracted from the MD database (Table 2.5). From each of these

Table 2.5 Statistics on the main metallogenic types found in EU and their tonnage (endowment) for their three main commodities (by order of decreasing frequency within the deposit type)

Metallogenic type		Number of deposits	Ratio of commodities with documented potential (%)	Commodity 1		Commodity 2		Commodity 3	
Type number	Name			Name	Total tonnage	Name	Total tonnage	Name	Total tonnage
1	Alkaline and peralkaline intrusions	30	34.1	U	95,892	REE	718,948	Nb	778,963
2	Epithermal	512	27.9	Au	2051	Ag	19,199	Pb	2,694,389
3	Igneous felsic	890	17.8	U	113,888	Sn	1,284,825	W	300,861
4	Igneous intermediate	131	35.6	Cu	41,168,901	Au	1939	Ag	18,406
5	Igneous replacement	390	42.6	Zn	14,384,048	Pb	21,141,522	Fe	244,433,280
6	IOCG	67	78.4	Fe	2,538,790,905	Cu	567,297	Mn	1,107,910
7	Mafic intrusion	45	72.0	Ti	171,207,562	V	373,052	Fe	325,582,230
8	Mafic or UltraMafic	641	47.5	Cu	2,625,595	Ni	2,682,432	Co	124,389
9	Orogenic gold	514	20.8	Au	1309	Cu	399,129	Ag	6,892
10	Pegmatites	349	7.3	Li	307,713	Feld	4,266,023	Be	680
11	Carbonate-hosted	641	19.6	Zn	34,832,297	Pb	9,404,228	Fe	427,871,659
12	Sandstone- and shale-hosted	322	31.3	U	438,927	Cu	92,663,587	Pb	2,119,515
13	Sedimentary deposits	630	35.9	Fe	8,501,259,818	Mn	14,752,044	Ni	3,531,669
14	VMS	820	54.6	Cu	27,240,890	Zn	79,963,991	Ag	59,925
15	Residual deposits	588	24.3	Al	933,038,160	Fe	239,478,322	Ni	6,227,977
16	Base metals veins	1947	21.7	Pb	17,859,114	Fl	36,033,304	Brt	31,647,820

Tonnage (endowment) is expressed in metric tons. Total number of deposits: 8994, representing 69.3 % of the database (12,979 deposits). Other deposits are either of undefined metallogenic type (insufficient information for establishing the type), or belong to the 'Rocks and Industrial Minerals' group, or to the 'Energy Commodities' (e.g. coal, oil and gas …) group or to minor types

(a)

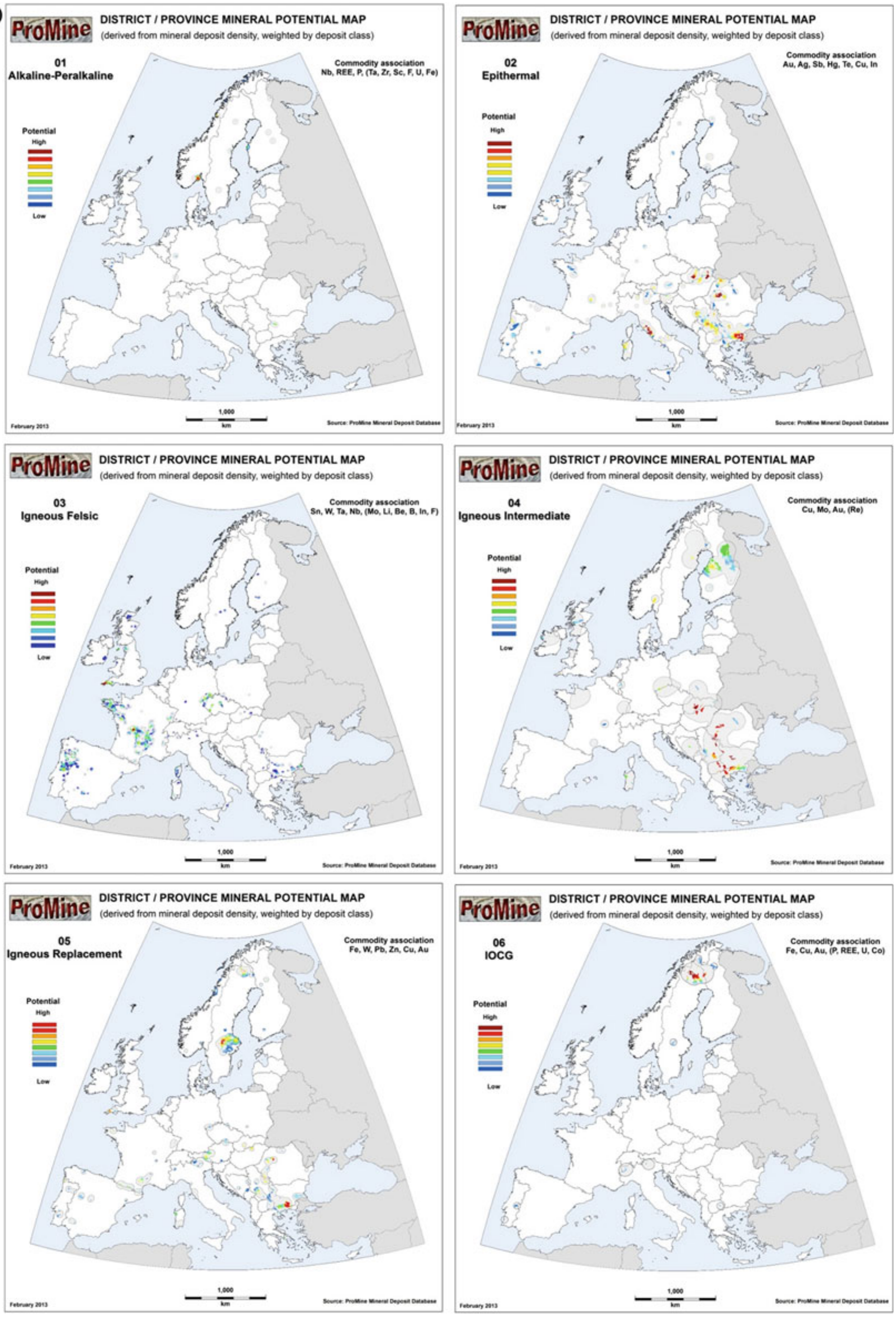


Fig. 2.5 **a** Map of mineral potential for commodity associations 1–6. **b** Map of mineral potential for commodity associations 7–12. **c** Map of mineral potential for commodity associations 13–16

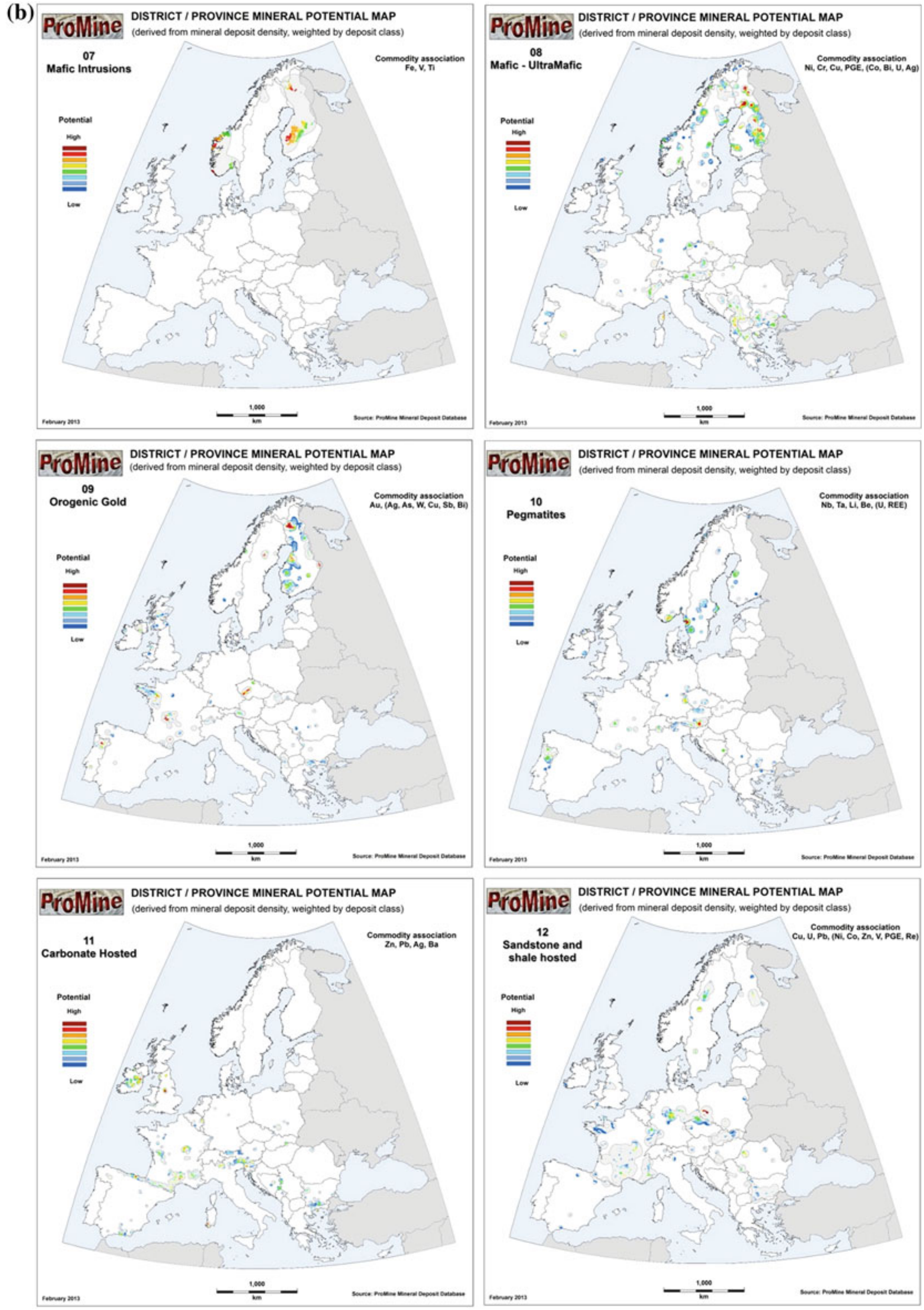


Fig. 2.5 (continued)

(c)

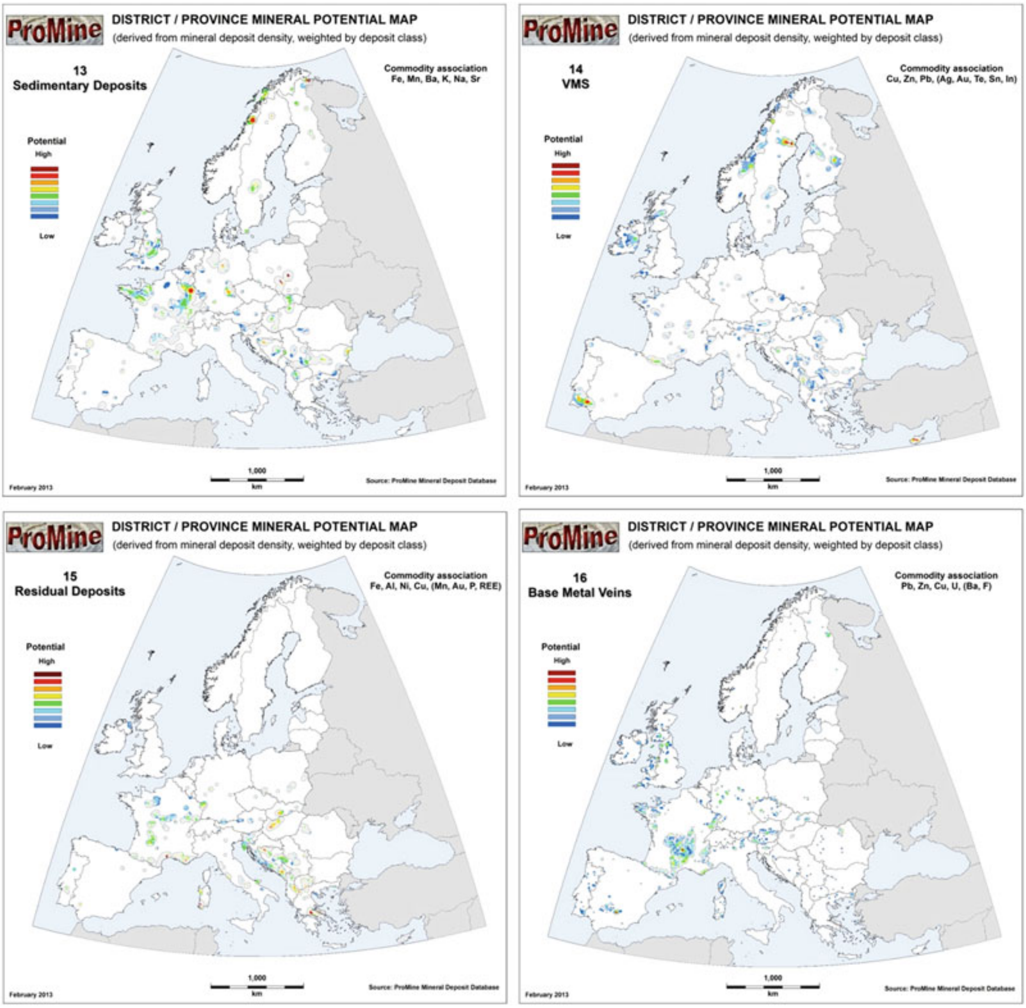


Fig. 2.5 (continued)

16 populations of deposits, a single map of mineral potential was calculated.

The methodology used to calculate these maps combine (1) a statistical study of the spatial distribution of deposits (kernel density[5] in a first stage), (2) geological constrains, by selecting lithology polygons containing deposits of the selected population (i.e. favourable lithologies) and (3) the introduction, as a weight, of the size (class of the main commodity) of the deposits (weight of 1 for showings and occurrences, 4 for small deposits, 9 for medium deposits, 16 for large deposits and 25 for very large deposits). The calculation made here—contrary to predictive mapping—does not involve probabilities. The weight used here is a single portrayal enhancer based on commodities classes (see Appendix 1) and whose five values have been graphically defined, the strict respect of magnitude of threshold values having led to hardly readable maps (over-representation of larger districts and disappearance of low potential districts). Grids so obtained are then combined in a potential map that images the weighted density

[5]Kernel density is a method to calculate the density of point (or line) features (deposits in our case) per unit area using a kernel function to fit a smoothly tapered surface to each point (or line).

of deposits in favourable lithologies. 16 potential maps were thus produced (Fig. 2.5a–c) to get a representation of the mineral potential of the 16 selected metallogenic types (Table 2.5). The importance of this methodical approach is that it could be used whatever the type and the density of deposits over large areas and yields consistent results at continental scale. The mineral potential maps are presented and discussed below. They show how the continental scale distribution of known mineralization derived from the ProMine MD database is consistent with the regional geological and tectonic context. This confirms the reliability of the database, and its scientific value for further studies.

2.4.2 Enhanced Mineral Potential Maps by Metallogenic Associations

The metallogenic associations considered herein are based on the 16 families identified by the ProMine consortium to describe the various European mineralization.

Group 01: Alkaline and peralkaline intrusions (Fig. 2.5a)

Theoretical commodity association: Nb, REE, P, (Ta, Zr, Sc, F, U, Fe)

The largest part of the Alkaline group (i.e. alkaline rocks and carbonatites) and its associated mineralization is located within the Fennoscandian Shield (Woolley and Kjarsgaard 2008; Woodard 2010). It includes geographically scattered deposits that were emplaced during various periods: (i) the Palaeoproterozoic (Katajakangas, Siilinjärvi), (ii) the Mesoproterozoic (Norra Kärr), (iii) Neoproterozoic (Søve and Alnö 580 Ma) and (iv) the Upper Palaeozoic (Sokli and Sæteråsen, Upper Devonian carbonatite and Permian trachyte, respectively).

In other parts of Europe, less important mineral deposits are present, such as Laacher See and Kaiserstuhl in Germany (related to the volcanism in the Rhine graben), Loch Borralan in Great Britain, or Svidviya syenites in Bulgaria.

Group 02: Epithermal and volcanic systems (Fig. 2.5a)

Theoretical commodity association: Au, Ag, Sb, Hg, Te, Cu, In

Minor epithermal and volcanic group potential can be found in the Fennoscandian Shield and western Europe Hercynian domain. On the other hand, the potential is much higher along the Tethyan suture, in south-eastern Europe, especially between Slovakia and Greece. This high potential province extends eastwards to Turkey and the Caucasus region (Georgia, Armenia, and Azerbaijan).

The westernmost typical epithermal deposits are associated with Miocene magmatism related to the opening and evolution of the western Mediterranean sea. They are represented by, for instance, the small Rodalquilar ore deposit in Spain (Arribas et al. 1995) and the north-western Sardinia mineral deposits (e.g. Calabona). The Latium district, in Italy, is the first group of some importance. It includes mineral deposits related to Plio-Quaternary volcanism, such as a fluorite-bearing ore deposit group (Pianciano) and a mercury- and/or antimony-bearing group (Monte Amiata and Tafone, respectively).

To the east, the various epithermal and porphyry districts (Cassard et al. 2004) of Upper Cretaceous (Lips et al. 2004) to Mio-Pliocene age (Neubauer et al. 2005) in the Carpathian-Balkan region are well known and form a semi-continuous belt which includes Kremnica in Slovakia, Telkibanya in Hungary, Baia Mare and Apuseni Mountains in Romania, Bor in Serbia, Assarel in Bulgaria and the eastern Rhodopes (Madan group in Bulgaria and Perama in Greece). Farther south, in the Balkan domain, epithermal type mineral deposits are more scattered. Of particular note is the Trepča district, in Kosovo, that combines carbonate-related and epithermal types.

Group 03: Igneous felsic (Fig. 2.5a)

Theoretical commodity association: Sn, W, Ta, Nb, (Mo, Li, Be, B, In, F)

The distribution of igneous felsic deposits and potential is mostly related to Hercynian granites and their associated ores (W–Sn, U and Mo mineralization, with Cu, Zn and Pb associated sulphur; Bouchot et al. 2000).

The major domains where these deposits are located fit with late-orogenic Hercynian leucogranites (Williamson et al. 1996). Five such domains follow the Hercynian arc (Ledru et al. 1994; Matte 1994; Franke et al. 2005) in Galicia-Portugal (W dominant), British Cornwall, French Brittany (Sn dominant) and French Massif Central, and western Bohemian Massif (Erzgebirge). They show a large variety of occurrences, especially intrusion-related peripheral polymetallic veins and uranium ore deposits (Marignac and Cuney 1999).

Outside these major districts are additional more scattered deposits in other Hercynian domains (e.g. Vosges and Black Forest, the Pyrenees, Corsica, Sardinia), Rhodopes (Bulgaria), the Caledonian belt (Great Britain and Norway) and the Scandinavian Precambrian domain.

Group 04: Igneous intermediate (Fig. 2.5a)

Theoretical commodity association: Cu, Mo, Au, (Re)

Igneous intermediate mineralization (i.e. porphyry type, Singer et al. 2008; Cooke et al. 2005) is typically related to the evolution of the western Tethyan suture in the late Cretaceous and Cenozoic, especially in Eastern Europe where there is high potential for additional deposits.

In Eastern Europe, the Upper Cretaceous in the Tethyan margin, contains large porphyry-type districts (Lips et al. 2004), of which most were subsequently reactivated and are associated with epithermal-type ores. The most important are Kremnica in Slovakia, Telkibanya in Hungary, the Apuseni Mountains in Romania, Bor in Serbia, Assarel in Bulgaria and Bucim in Macedonia.

Other domains also host porphyry-type mineralization, of older age, although their classification as belonging to this deposit type is still debated. In the Fennoscandian Shield, several Cu-(Au)- or Cu–Mo-bearing Palaeoproterozoic deposits are described as porphyry style. The most important are Aitik (Cu–Au) and Tallberg (Cu–Au, Skellefte district), both in Sweden, and Kopsa (Au–Cu) related to a tonalite stock in the Hitura belt (in Finland).

In relation to the Caledonian volcanism, there are a few smaller porphyry-type deposits of Lower Palaeozoic age in Great Britain, such as Coed y Brenin (Wales) and Black Stockarton Moor (Scotland).

Hercynian magmatism in the Upper Palaeozoic is associated, especially in France, with Cu–Mo–W porphyry deposits, although their geodynamic context is poorly described (e.g. Beauvain, Mo; Sibert, Cu; Auxelles-le-Haut, W).

There are also porphyry Mo mineral of various ages in Europe. The most important of these is probably Nortli in Norway (Sandstad et al. 2012), a group of deposits related to Permian intrusions in the Oslo rift.

Group 05: Igneous replacement or skarn (Fig. 2.5a)

Theoretical commodity association: Fe, W, Pb, Zn, Cu, Au

Igneous replacement or skarn deposits (Einaudi et al. 1981) occur where carbonate rocks are cut by younger intrusions. In Europe, they are distributed in three major domains: (i) the Precambrian Fennoscandian Shield, (ii) the Hercynian domain in southern Europe, and (iii) the Cenozoic Carpathian-Balkan domain.

The Fennoscandian Shield contains iron deposits in greenstones of the Lappland Palaeoproterozoic domain (e.g. Puoltsa, Sautusvaara and Stora Sahavaara in Sweden, Kolari district in Finland). These deposits are related to ‘magnetite-enriched formations and Ca–Mg calc-silicates’, spatially associated with BIFs or Kiruna type IOCG. Recent studies in the Kolari area in Finland (i.e. Laurinoja and Kuervitikko Rautuvaara) show that metasomatized replacements are preferentially IOCG type facies rather than typical ‘intrusion-related skarn deposits’. In the Bergslagen district in Central Sweden skarn mineralization is hosted by Palaeoproterozoic marbles intruded by post-tectonic granites

(~1.8 Ga). Examples of such deposits include the Yxsjöberg (Hallberg et al. 2012) "scheelite-skarn deposit", skarn iron lenses and skarn iron-sulphides lenses of Stollberg (Fe–Pb–Zn–Mn (Ag)), and sulphide skarn of Garpenberg (Zn). The Arendal (Klodeborg) iron deposit in Norway comprises magnetite skarn in Mesoproterozoic sequences (~1.2–1.5 Ga) cut by younger intrusions (~0.9–1 Ga), and the Knaben deposit (same age) is located in gneisses, paragneisses and amphibolites.

In the southern part of the Hercynian domain, well developed Palaeozoic (Cambrian and Devonian, essentially) carbonate layers and Hercynian (Upper Carboniferous, ~310 Ma) magmatism allowed the development of tungsten- (and/or magnetite-) bearing skarns in the Pyrenees, the southern Massif Central, in Sardinia and in the Alps. The northern parts of the Hercynian arc display only minor occurrences, essentially because of the lack of Palaeozoic carbonate units.

In the Balkan-Carpathian domain, numerous carbonates, essentially of Mesozoic age, and Upper Cretaceous-Cenozoic magmatic episodes allowed development of numerous replacement deposits in the vicinity of epithermal and porphyry domains. Important examples include Kremsica, Baia Mare, Bor, Madan and Trepča.

Minor deposits of this group can also be found in the western Mediterranean, related to Tertiary and Quaternary magmatic episodes in Spain, Sardinia (e.g. Calabona skarn associated with a dacitic porphyry copper) and close to Elba.

Group 06: IOCG (Fig. 2.5a)

Theoretical commodity association: Fe, Cu, Au, (P, REE, U, Co)

This type of mineralization can be found essentially in two Palaeoproterozoic districts in the Fennoscandian Shield (Weihed 2001). The most important is Kiruna (northern Sweden), which is a type locality for IOCG, and the other one is Bergslagen (central Sweden). These districts contain large world-class iron deposits, with a typical magnetite-apatite paragenesis and sodium alteration. These districts also contain copper sulphide deposits that are interpreted as VMS (Viscaria) or porphyry (Aitik; Wanhainen et al. 2005).

More limited IOCG style deposits are also known in other parts of Europe. Some Fe (Fe–Cu) IOCG style deposits are identified in the Ossa Morena Zone in southwestern Iberia. They are mesozonal albitite-related magnetite deposits and are interpreted (Tornos et al. 2005) as being related to either residual melts of rift-related juvenile magmas (Cambrian) or anatexis of earlier mineralization during high T/low P metamorphism along major shear zones of Variscan age.

Group 07: Mafic intrusion (Fig. 2.5b)

Theoretical commodity association: Fe, Ti, V

This type of deposit is clearly associated with Precambrian rocks in the Fennoscandian Shield, with groups varying in age from one district to another.

In Finland, these deposits are of Palaeoproterozoic age and are related to mafic complexes, in the Karelian domain, that were emplaced during several episodes of rifting triggered by mantle plume activity. To the north, deposits of chromite, vanadium, titanium, platinum-group elements are located along the boundary of the Archaean domain. They are related to stratified mafic complexes of Siderian age (~2.44–2.5 Ga). The Mustavaara deposit (Eilu et al. 2012) displays a typical stratified sequence composed of (from bottom to top) a marginal zone, then layers of pyroxene-gabbro, anorthosite-gabbro, magnetite-gabbro, and anorthosite-gabbro again.

Younger Palaeoproterozoic deposits, such as Otanmäki (Fe–Ti–V) of Rhyacian age (2060 Ma, Talvitie and Paarma 1980) and the Kauhajarvi gabbro complex (1874 Ma, Kärkkäinen and Appelqvist 1999) occur farther south in Finland.

Farther west in the Fennoscandian Shield, deposits of this type are essentially of Sveconorwegian age (Late Mesoproterozoic-Early Neoproterozoic). They could be equivalent to the Greenvillian Ti–V anorthosites in Canada. The main deposit is Tellness, in the Rogaland province of Norway (the major plutonism took place between 932 and 920 Ma, 50–60 Ma after the last major regional deformation; Schärer et al. 1996). Bamble and Arendal, and probably Selvag, are also of late Sveconorwegian age (~990 Ma).

In Norway, some deposits were emplaced during late Palaeoproterozoic-early Mesoproterozoic, such as Raudsand (or Rødsand), in the Møre province (1.7 Ga) and some in the Lofoten (1.9 Ga). Similar Precambrian deposits that was later affected by the Caledonian orogeny can also be found, such as at Bergen (Norway) and Routevare (Sweden). They are related to Precambrian anorthosites (~1.78–1.76 Ga, Rehnström 2003). In Norway, the Kodal deposit (P–Fe–Ti) is related to Permian magmatism in the Oslo graben. This deposit however also shows alkaline characteristics (basalts and jacupirangites).

In Poland, the Suwalski (or Krzemianka) Fe–Ti–V deposit (Morgan et al. 2000) is related to an anorthosite-norite Mesoproterozoic (~1.5 Ga) intrusion and is similar to deposits in the Fennoscandian Shield. It is located in the deep Precambrian basement, at approximately 1000 m depth.

Group 08: Mafic-Ultramafic (Fig. 2.5b)

Theoretical commodity association: Ni, Cr, Cu, PGE, (Co, Bi, U, Ag)

Major deposits of this type are located in the Fennoscandian Shield mainly in the Karelian area. They are related to the main rifting pulse and plume activity of the early Palaeoproterozoic (Weihed et al. 2005). These deposits are located in Finland (i) in the Kemi district (Kemi, Cr; Sompujarvi, Pt; Siika-Kama, Pd and Suhanko, Pd); (ii) in Kevitsa (Ni) and Koitelainen (Cr), (iii) in the Uutela district (talc), (iv) in Hitura (Ni), Kotalahti (Ni) and Laukunkangas (Ni), and (v) farther south in Vammala (Ni) and Petolahti (Ni).

Other deposits (Sandstad et al. 2012) can be found in the Sveconorwegian domain (~1000–900 Ma). They are related to Ni–Cu sulphur-bearing deformed noritic intrusions in Rana, Flat and Ertelien (Norway). They were probably emplaced during an early rifting stage of the Sveconorwegian orogeny (equivalent to Grenvillian in Canada).

Several deposits in Norway are related to the Scandinavian Caledonian domain. These include: (i) Altermark (talc) in Norway, (ii) the nickel district of Stekenjokk (Njeretjakke), with Cu–Ni sulphur (and PGE + Au enrichment in Stormyrplutten and Lillefjellklumpen) in Lower Ordovician basalts and gabbros, and (iii) the Rana deposit (Cu–Ni sulphur) related to a mafic-ultramafic intrusion.

This type of deposit is uncommon in Palaeozoic rocks. One exception is the Cu–Ni sulphur deposit of Aguablanca (Tornos et al. 2005) located in a mafic breccia pipe intrusion (of Lower Carboniferous age) fed by a mid-crust mafic-ultra mafic stock. It contains pyrrhotite, pentlandite and chalcopyrite formed from the crystallization of an immiscible sulphide-rich liquid.

In the 'ultramafic' type, other deposits which should be included are: (i) the Amaden mercury deposit, which formed from the activity of a Silurian mantle plume (Higueras et al. 2005; Jebrak et al. 2002) although the host-rock is sedimentary to volcano-sedimentary and (ii) the 'five elements' vein deposits (Bi, Co, Ni, Ag, U), such as Jachymov in Czech Republic, which have a mafic to ultramafic signature.

Finally, in the Balkan domain and in Greece, various deposits in the Mesozoic ophiolites are associated with ultramafic bodies (talc, magnesite, lateritic nickel, chromite lenses).

Group 09: Orogenic gold (Fig. 2.5b)

Theoretical commodity association: Au, (Ag, As, W, Cu, Sb, Bi)

The distribution of deposits of this type (Groves et al. Groves et al. 1998) is relatively straightforward as it is characterized by a single main commodity and a well-constrained type of mineralization. Major known gold-bearing districts belong to two groups:

- Palaeoproterozoic orogenic deposits (Eilu et al. 2003; Eilu and Weihed 2005) in the Fennoscandian Shield;

- Hercynian gold-bearing districts (Bouchot et al. 1997, 2005) related to late Hercynian (~300 Ma) deformation belts, especially the deposits in the northern Iberian Peninsula, the French Massif Central and the Bohemian Massif.

Additional more scattered deposits can be found in other Hercynian domains (e.g. Salsigne in southern France, Lescuyer et al. 1993), the Caledonian domain (Great Britain and Norway) and the Balkan-Carpathian domain.

Group 10: Pegmatite (Fig. 2.5b)

Theoretical commodity association: Nb, Ta, Sn, Li, Be, (U, REE)

This group is related to the igneous group as it represents its peripheral and shallow expression (Cerný and Ercit 2005). This explains the very similar distribution of deposits of both groups.

In the Fennoscandian Shield, pegmatite deposits are related to Palaeoproterozoic (Svecokarelian) magmatism in southern Sweden and Finland, and Sveconorwegian (end of Mesoproterozoic) magmatism to the southwest of the shield (Sweden, Norway).

In the Variscan zone, most deposits are related to the late-Variscan magmatism, especially in the tungsten and/or tin provinces, i.e. (i) in north-western Iberian Peninsula (Hesperids domain, Portugal, Spain), (ii) in Cornwall, (iii) in Brittany, (iv) in the northern part of the French Massif Central, and (v) in the eastern Alps (Austria). Beside these major groups, additional pegmatite deposits can be found in most other Palaeozoic ranges (e.g. the Pyrenees, Corsica, Vosges Mountains and Bohemian Massif).

Group 11: Carbonate-hosted (Fig. 2.5b)

Theoretical commodity association: Zn, Pb, Ag, Ba

This group includes not only deposits characterized by carbonated host rocks but also and essentially MVT (Mississippi Valley Type) deposits. Numerous Pb–Zn (Ba–F) deposits are located along the boundary between Hercynian basement and the Mesozoic transgression (Muchez et al. 2005). They are hosted by Palaeozoic, Triassic or Liassic limestones. In northern Europe, deposits are located in two areas:

- In Great Britain (F–Ba–Zn–Pb) where they are hosted by Palaeozoic basement and related to Triassic transgression in Derbyshire and northern Pennines;
- In upper Silesian district (southern Poland) where they are hosted by Triassic limestones with a multiphase reworking of mineralization that includes intense weathering and karstification during the Tertiary.

The most extensive belt of carbonate-hosted deposits is located in southern Europe from Galicia, in Spain, to the Central Alps (with possible extension into eastern Europe and Greece). It combines (i) Palaeozoic mineralization hosted by Cambro-Ordovician (Eastern Pyrenees, French Montagne Noire, Iglesiente in Sardigna) and Devonian carbonates (Central Pyrenees), (ii) mineralization related to Triassic transgression, and (iii) Mesozoic reactivation of this belt during normal faulting and rifting along the alpine Tethyan margin. Major deposits in this belt are, from west to east, Caravia (Trias), Rubiales (Cambrian) Reocin (Aptian), Pierrefitte (Ordovician, Devonian), Escarro (Cambrian-Ordovician), Les Malines (Trias), Croix de Pallières, Menglon, La Plagne, Gorno (Permian-Trias) Salafossa (Trias), Idrija (Hg in Trias), Mezica (Slovenia, in Trias). Farther east, in Greece and the Balkan, various deposits combine carbonated host rock and replacements processes (e.g. Sedmochislenitzi, Madan in Bulgaria; Olympias-Kassandra, Laurium in Greece).

A specific case is the Navan district (Ireland), which is related to exhalative zinc deposits (type 14), but hosted by Carboniferous limestones (Anderson et al. 1998; Ashton 2005).

Group 12: Sandstone and shales hosted (Fig. 2.5b)

Theoretical commodity association: Cu, U, Pb, (Ni, Co, Zn, V, PGE, Re)

This type includes the major copper mineralization in the Kupferschiefer Permian sediments

(Oszczepalski and Blundell 2005; Hitzman et al. 2010). This type of mineralization mainly occurs in southern Poland (Lubin district), but also in Germany (Mansfeld, Richelsdorf, Spremberg). It also includes the Palaeoproterozoic metamorphosed black shales of Talvivaara in Finland (Ni, Co, Cu). These deposits were the subject of specific studies in the ProMine project aimed at testing ore bioleaching processes.

This type also includes uranium deposits hosted in sandstones and schists of various ages. The main of potential are related to (i) uranium deposits of Tåsjö, Myrviken and Ranstad (alum shales) in relation with Cambro-Ordovician schists and sandstones (Sweden); (ii) Late Hercynian (Permian) deposits (e.g. Lodève half-graben in France, and Bulgaria), (iii) Cretaceous limestones (Cenomanian) in the Hamr-Liberec district (Czech Republic), and (iv) the Coutras Eocene sandstones (France).

In addition to these typical Cu- or U-bearing mineralization, numerous Pb, Ba and/or F mineral deposits are hosted in sandstones in a transgressional context (e.g. Triassic), along the margin of Hercynian basement.

Group 13: Sedimentary deposits (Fig. 2.5c)

Theoretical commodity association: Fe, Mn, Ba, K, Na, Sr

The distribution of deposits from this type is essentially controlled by iron sedimentary deposits. They include Scandinavian BIFs and Jurassic oolitic iron deposits in England (e.g. Northampton), France (e.g. Lorraine), Germany (e.g. lower Saxony), Belgium (e.g. Campine), Poland (e.g. Silesia), etc.

This type also includes less common Palaeozoic deposits (e.g. Carboniferous in Great Britain, Cambrian and Ordovician in France and Iberian Peninsula).

The only important non-ferrous sedimentary group comprises Oligocene manganese deposits in the Obrochishte district (Bulgaria), near the Black Sea.

Group 14: VMS (Volcanogenic massive sulphide deposits) (Fig. 2.5c)

Theoretical commodity association: Cu, Zn, Pb, (Ag, Au, Te, Sn, In)

The distribution of deposits of this type clearly highlights the major known VMS type provinces:

- The Palaeoproterozoic districts of Skellefte and Bergslagen, in Sweden, and Vihanti-Pyhäsalmi and Outokumpu, in Finland (Weihed and Eilu 2005)
- The Upper Palaeozoic (Devonian, Carboniferous) district of the southern Iberian province (e.g. Rio Tinto in Spain, Neves Corvo in Portugal) in Spain and Portugal (Leistel et al. 1998)
- The Upper Cretaceous VMS district in Cyprus (Skouriotissa, Mavrovouni, Limni), related to the Troodos ophiolite complex (Jowitt 2008)

In addition to these three major mineralized provinces, there are several other smaller deposits:

In Scandinavia, copper-rich stratiform sulphides formed in the Palaeozoic along the Caledonian domain. They could be VMS deposits of various types (e.g. Röros VMS in back arc setting, Tverrfjellet and Joma VMS of Besshi type, Sulitjelma VMS of Cyprus type). These mineral deposits seem to extend southward into the Dalradian Caledonian domain of Scotland (e.g. Ben Collum, Auchtertyre).

Other VMS mineralization, of Devono-Carboniferous age, can be found in the European Hercynian domain. In France (Châteaulin basin, Saint-Georges-sur-Loire and Chessy), several volcanic related deposits have ages similar to those in the southern Iberian Province (Upper Devonian and Tournaisian). Their tonnages, however, are much smaller. In other parts of the Hercynian domain, massive sulphide deposits are preferentially of SEDEX type (e.g. Rammelsberg and Meggen in

Germany, Rhinish-Hercynian domain; Large and Walcher 1999; Schneider 2005). In the Navan district (Ireland), they are hosted in a Carboniferous foreland sedimentary basin.

In addition, there are also numerous mineral deposits or groups of mineral deposits (with various commodities) where the classification is still debated. This is the case, in particular, for iron deposits in the Alps and the Balkan-Carpathian domain that were classified as SEDEX. They could in fact be replacement deposits (e.g. Ljubija and Omarska in Bosnia and Herzegovina, Erzberg in Austria). Mercury and copper deposits (e.g. Idrija in Slovenia, Munella in Albania), classified as SEDEX could also be epithermal.

Group 15: Residual Deposits (Fig. 2.5c)

Theoretical commodity association: Fe, Al, Ni, Cu, (Mn, Au, P, REE)

This type of deposit shows a significant geographic control and is found essentially in southern Europe. The main types of deposits are bauxites, lateritic nickel, residual concentration in carbonated ores (Mn, Fe a.o.), or gossan-type concentration from sulphides ore (Cu, Au a.o.).

Bauxites develop in emerged domains, in relation to the alteration (essentially from Upper Cretaceous to Palaeogene) of an older carbonate basement (essentially Triassic to Lower Cretaceous). They result from the palaeogeographic and climatic evolution of the Tethyan margin during this period. The main bauxitic domains are to the west, the northern Pyrenean and Provence domains (Villevayac, les Baux) and to the east, the Balkan domain (e.g. Niksic in Montenegro, Mostar in Bosnia and Herzegovina, and the Giona-Parnassus district in Greece) and Hungary (Fenyöfö, Nyirád district).

In ophiolitic series of the Balkan domain, some nickel lateritic mineral deposits formed as a result of the alteration of silica. Examples of such deposits are Citakovo-Glavica in Serbia, Rzanovo in Macedonia, Evia (or Madu di Limni) and Aghios Ioannis (or Larimna) in Greece. Nickel residual deposits (e.g. Szklary en Poland) also formed from older Variscan ophiolitic mafic or ultramafic rocks.

Some deposits have residual concentrations significantly enriched, relative to primary ores. Examples include: Mn (e.g. Urkút in Hungary), Fe (Ljubija in Bosnia), Zn (Iglesiente district in Sardinia), Cu and/or Au (e.g. Las Cruces, southern Iberian Province; Rudno and Banska, porphyry and epithermal provinces of Slovakia; Rouez in France, etc.)

Group 16: Polymetallic veins (Fig. 2.5c)

Theoretical commodity association: Pb, Zn, Cu, U, (Ba, F)

Underground extraction in mineralized veins is the oldest mining industry in Europe. It extends in time from the Middle Ages to the twentieth century, with the geographic distribution of mined deposits controlled not only by mining criteria but also by culture and history. This mining activity mainly took place in the Hercynian domain, from the Bohemian Massif (Czech Republic) to France. Potential mapping of these deposits shows a heterogeneous distribution with an over-representation of France relative to its neighbouring countries (compare for instance the Vosges and Black Forest Mountains on both sides of the Rhine graben).

These polymetallic vein deposits are related to the Hercynian orogeny (e.g. Bouchot et al. 2005). The main vein-types are (i) Pb–Zn–Cu–Ag veins extracted since the Middle Ages essentially for silver (famous districts, such as the Erzgebirge, the Vosges Mountains, the Black Forest), (ii) antimony veins in the Brioude-Massiac district (France), (iii) peripheral tin and tungsten veins near felsic intrusions (e.g. Portugal, France and Cornwall), (iv) fluorite and barite low temperature veins along the border of the Hercynian domain (e.g. France).

There are also uranium veins in two Hercynian domains (French Massif Central and Czech Bohemian Massif). The high frequency of such uranium deposits in some countries (e.g. France, L'Escarpière district; Czech Republic, Pibram district) partly results from intense prospection work carried out to support specific government policies at various times.

2.5 Mineral Predictive Mapping

Methodologies used for the calculation of mineral predictive maps are numerous (see review in Carranza 2011) and vary depending on a range of factors, for instance, and this is particularly true for 'strategic' commodities, whether the targeted commodity is a main element in the deposit or a by-product. Up to now, the majority of predictive studies have dealt with only a few elements which are the main commodities in the deposits and/or which belong to the main paragenesis. Examples include copper and gold in porphyries (Bougrain et al. 2003; Billa et al. 2004; Roy et al. 2006), gold and silver in epithermal deposits (Carranza 2009a), orogenic gold deposits (Knox-Robinson and Groves 1997; Bierlein et al. 2006; Nykänen et al. 2008), iron oxide copper gold deposits (IOCG—Nykänen 2008) or gold placers (Cassard et al. 2008) and, more recently, uranium (Kreuzer et al. 2010). However, the ProMine project paid particular attention to strategic and critical commodities, especially to the 14 critical raw materials identified by the European Commission (2010), which may or may not be the main commodity within a given deposit.

In practice, these strategic or critical raw materials are either major constituents of the ore minerals that are actually mined (e.g. tungsten, antimony, fluorite, tin) or commodities which are by-products from mining of major metals (e.g. germanium, indium, gallium, tantalum). As a consequence, the predictive methods used have to be adapted to take account of both possibilities. In this study we used, for the first case, a geographic prediction method (Weight of Evidence, or WofE) and, for the second case, a database querying method, which has been specifically developed for the ProMine project.

The WofE method was applied to identify areas favourable for tin, tungsten, antimony, fluorite, copper and a selection of lead-zinc carbonate-hosted deposits. The same data processing was used for all these commodities. The database querying method was applied to explore the relationships between descriptive fields of the database (i.e. what best characterizes the deposits that contain the targeted commodity), and to predict those deposits, of the 13,000 in the database, possibly containing cobalt, gallium, germanium, indium and tantalum. One should note that, in the latter case, it implies that this method identifies and ranks deposits in the database that might be regarded as potential sources of the targeted by-product commodity, but does not map the favourability around these sites.

2.5.1 Predictive Mapping of Favourable Host Rocks for Main Commodities Using the Weight of Evidence (WofE) Method

2.5.1.1 Methodology for the Weight of Evidence Method

The WofE method is a probability-based approach (Bonham-Carter et al. 1989; Bonham-Carter 1994) that uses Bayes' rule to combine evidence with an assumption of conditional independence. This method requires, on a specific area, a set of training points (mineral occurrences) and a coverage of polygons (geological map). Where sufficient data are available, it can be applied to estimate the relative importance of evidence by statistical means. Calculating the WofE on a geological map, covering several geological formations, is similar to using a multi-class evidential theme. The calculation of WofE characterizes each formation by three numerical values: W+, W− and C (see Bonham-Carter (1994) and Kemp et al. (2001) for details of these calculations). The positive and negative weights (W+ and W−) provide a measure of the spatial association between the training points (in this case the mineral deposits of the particular target type) and the evidential theme (in this case, the lithostratigraphy polygons). A weight is calculated for each class of the evidential theme:

In these equations:

- D is the number of unit cells containing a prospect or deposit (training point);
- B is the number of unit cells containing a given formation b;
- $P(B \mid D)$ is the probability of occurrence of formation b, given the condition of being on a deposit;
- $P(B \mid \overline{D})$ is the probability of occurrence of formation b, given the condition of not being on a deposit;
- $P(\overline{B} \mid D)$ is the probability of non-occurrence of formation b, given the condition of being on a deposit;
- $P(\overline{B} \mid \overline{D})$ is the probability of non-occurrence of formation b, given the condition of not being on a deposit.

The absolute value of a weight indicates whether a criterion is slightly significant ($0 < W < 0.5$), significant ($0.5 < W < 1$), very significant ($1 < W < 2$), or discriminant ($W > 2$). The contrast, C, which is the difference between the weights ($C = W+ - W-$), is an overall measure of spatial association between the training points and the evidential theme, combining the effects of the two weights.

The spatial analysis was performed on the training points and lithostratigraphy layers, using the Arc-SDM (Spatial Data Modeller) extension (Kemp et al. 2001), developed for ESRI®'s ArcView 9.x / Spatial Analyst. The same process was used for all targeted commodities (i.e. tungsten, antimony, fluorite and tin, copper and a selection of Pb–Zn carbonate hosted deposits). Weights were calculated separately for deposits (i.e. class A, B, C, D, E) and showings (i.e. class N/A) in the database. Results were added as follows: (Weight of deposits) + 0.5 (Weight of showings).

In conclusion, WofE modelling has been performed on one evidential theme, the lithostratigraphy which has been carefully homogenized when preparing the 1:1,500,000 ProMine geological background map. Other available 'layers'—e.g. structural (resulting from generalization), geophysical etc.—are not enough accurate at this scale, and their use would have brought no real improvements, but possible artefacts. In general, the results confirm the interest of already known areas. New areas/sectors of possible interest resulting from this study generally make sense in terms of geological context. They will, however, need to be confirmed in the future by field work.

2.5.1.2 Predictive Mapping of Favourable Host Rocks for Selected Main Commodities

Tungsten

280 deposits containing tungsten were used: 41 deposits in which W is the main commodity, and 239 showings (i.e. occurrences with W minerals present, but without any resource indication). Among them, the dominant deposit types are igneous felsic (56 %) and igneous replacement (23 %). The dominant associated commodity is tin (e.g. Cornwall, UK; Moon 2010).

Most results are located within the Palaeozoic domain (Fig. 2.6a) of Iberia (e.g. Panasqueira in Portugal, Noronha et al. 1991; Los Santos in Spain, Sánchez et al. 2009), the French Pyrenees (e.g. Salau, Costabonne, in Autran et al. 1980), the French Massif Central (Leucamp-La Châteigneraie district, Lerouge and Bouchot 2005), the Austrian Alps (Mittersill-Felbertal; Raith and Stein 2006) and the Bohemian Massif (e.g. Erzgebirge Sn–W Zinnwald district; Webster et al. 2004). In the Fennoscandian Shield, some results are related to the Archaean and Palaeoproterozoic metavolcanic greenstones cut by granitic intrusions (e.g. the Yxsjöberg W–Mo skarn deposit; Romer and Öhlander 1994; Hallberg et al. 2012). Favourable results are found mostly in: (i) sandstones and shales with Lower Palaeozoic carbonate

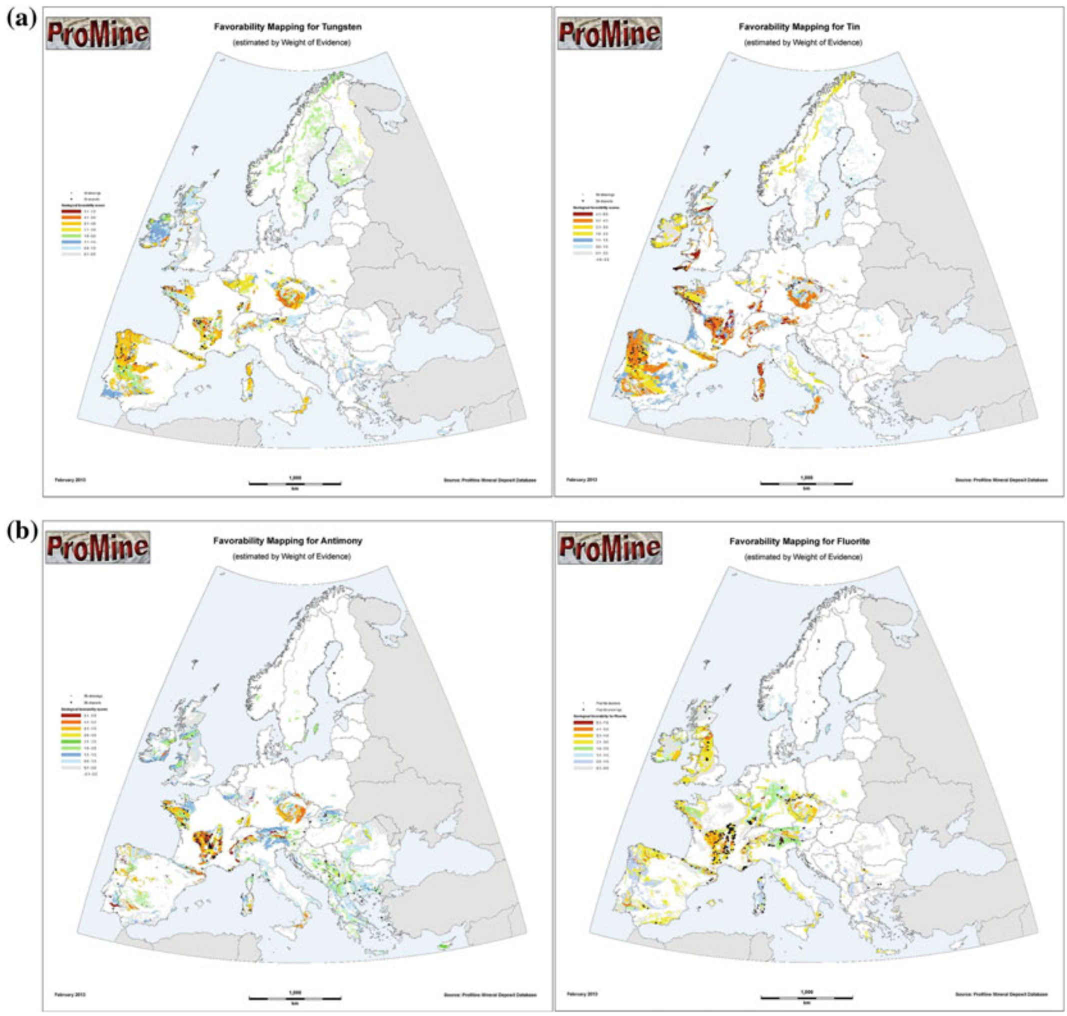


Fig. 2.6 **a** Maps of favourability, estimated with the weight of evidence method, for tungsten (*left*) and tin (*right*). **b** Maps of favourability, estimated with the weight of evidence method, for antimony (*left*) and fluorite (*right*). **c** Maps of favourability, estimated with the weight of evidence method, for zinc in carbonate hosted deposits (*left*) and copper (*right*)

(c)

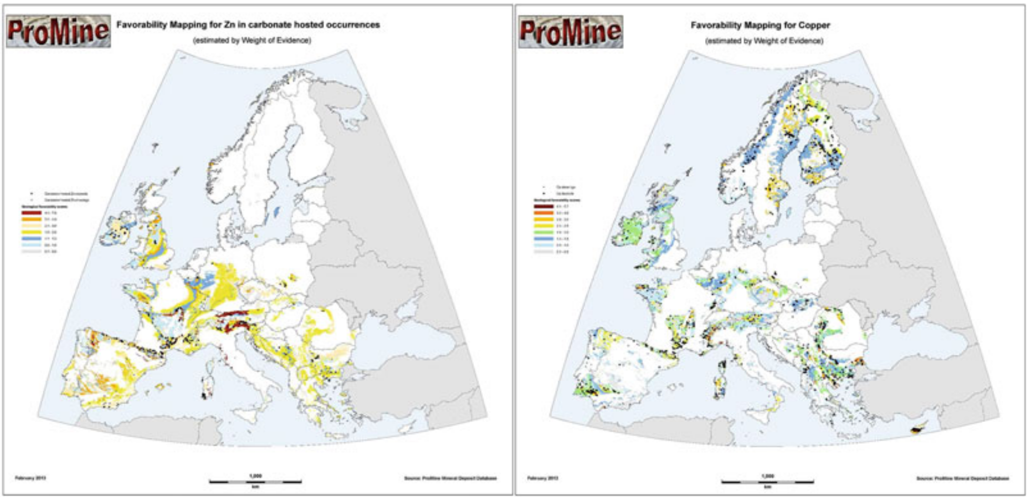


Fig. 2.6 (continued)

intercalations (Infra Cambrian, Cambrian and Ordovician), and (ii) Devonian sedimentary series with intercalated carbonates or Carboniferous granitic intrusions.

The map of favourable areas obtained with the WofE method, along with the density of known W-bearing deposits, allows favourable domains to be delineated in areas where no or few occurrences are known, such as the eastern Bohemian Massif, the Black Forest and the southern Iberian Peninsula.

Tin

252 deposits containing tin were used: 67 deposits in which Sn is the main commodity, and 185 showings (i.e. occurrences with Sn minerals present but without any resource indication). Among them, the dominant deposit types are igneous felsic (72.5 %) and pegmatite (9.5 %). The dominant associated commodity is W, along with, in smaller proportions, As, In, Zn and Mo.

The results highlight the importance of Upper Palaeozoic Hercynian intrusions (Fig. 2.6a), especially the late Upper Carboniferous leucogranites (~300 Ma). The Palaeozoic host rocks of these granites also appear favourable, especially Lower Palaeozoic sandstone-rich series. In the Fennoscandian Shield most favourable areas are located in the Palaeoproterozoic Svecokarelian (~1.9 Ga) volcano-sedimentary belts and in the Neoproterozoic sandstones and metagreywackes of the Caledonian belt.

Besides the usual tin provinces (e.g. Cornwall, UK, north-western Iberian Peninsula, French Brittany; Derre 1982; Plimer 1987), the results highlight several favourable areas, such as the north-western French Massif Central, Calabria, the eastern Bohemian Massif and several Neovariscan Carpathian massifs.

Antimony

342 deposits containing antimony were used: 109 deposits in which Sb is the main commodity, and 233 showings (i.e. occurrences with Sb minerals present but without any resource indication). Among them, the dominant deposit types are base metals veins (55.05 %), epithermal (17.8 %), orogenic gold (8.78 %) and, with a much lower importance (<5 %), carbonate hosted deposits and VMS. The dominant associated commodities are Au and As, along with, in smaller proportions, the (Pb, Zn, Cu, Ag) group and Hg in epithermal parageneses.

The main areas of favourability are located in the French Hercynian domain [Massif Central and southern Brittany, respectively the Brioude-Massiac district (Bril 1982), and the Vendée district (Bailly et al. 2000)] and correspond to late orogenic veins (~300 Ma) on Palaeozoic basement (Fig. 2.6b). The dominant host rocks are Lower Palaeozoic clastic metasediments and Upper Palaeozoic (including Devono-Carboniferous) volcanics. Another area favourable for Sb is the Carpatho-Balkanic region, in relation to Mesozoic and Cenozoic rocks (including volcanic). In summary the result allow Sb favourability to be defined in several areas of the Palaeozoic (e.g. Wales, the Alps, eastern Bohemia) and Balkan-Carpathian domains.

Fluorite

407 deposits containing fluorite were used: 113 deposits in which fluorite is the main commodity, and 294 showings (i.e. occurrences with fluorite mineralogy but without any resource indication). Among them, the dominant deposit types are base metals veins (70 %), carbonate-hosted (16.6 %) and igneous felsic (6.65 %). Fluorite is rarely present in other deposit types. The dominant associated commodities are Ba, Pb and Zn, and to a smaller degree Cu.

Fluorite mineralisation was emplaced during several periods. It is associated with plutonism and volcanism of various ages (Fig. 2.6b). This association with volcanic facies is a characteristic feature of fluorite mineralization. Two major periods of mineralization can be identified: (i) early Palaeozoic stratabound deposits (Infracambrian to Ordovician; e.g. Escarro in French Pyrenees) and (ii) the transitional period between Upper Hercynian (igneous, veins; e.g. Le Burg-Montroc in Montagne Noire, France) and Lower Mesozoic (veins, carbonate-hosted deposits; e.g. Pierre-Perthuis, France).

One should note also the fluorite associated with Quaternary volcanism in Latium (Barbieri et al. 1977). Scandinavian deposits are very scattered within huge domains and therefore are not conspicuous on the map.

Most favourable areas identified with the WofE method contain known fluorite occurrences. The predictive role of the map is therefore limited, allowing only the identification of scattered smaller domains (e.g. Calabria and Sicilia in Italy, Galicia and Aragon in Spain, northern England).

Carbonate-Hosted Zinc

In this case the problem is slightly different as the goal is not directly to seek the critical commodity, but to identify deposits that may contain germanium (i.e. zinc-bearing carbonate-hosted deposits). However, the methodology applied remains the same.

Commodity association corresponds to a usual paragenesis [i.e. Zn, Pb, Ag, Ba, (Cu, Ga)], and includes germanium in 7 % of selected deposits.

641 carbonate-hosted deposits containing zinc were used: 186 deposits in which Zn is the main commodity, and 455 showings (i.e. occurrences with Zn mineralogy but without any resource indication).

The results show clusters of deposits (Fig. 2.6c) related to carbonate series of Cambro-Ordovician (e.g. Iglesiente in Sardinia) and Devonian (e.g. French Pyrenees) ages, and series along the boundary between the Hercynian basement and the Mesozoic cover, especially the Liassic and Triassic formations (e.g. the Cevennes border in southern France).

The results also highlight domains where Zn-bearing carbonate-hosted deposits are known. They also extend favourable areas into contact zones between basement and sedimentary cover where no mineralization is known. This is the case, for instance, in the north-western French Massif Central, the Liassic margin of Normandy and the northern Hercynian domain in Germany.

Copper

Cu is a common commodity in the ProMine MD database: in the selected dataset, 22 % of deposits contain copper. 1777 deposits containing copper were used: 722 deposits in which Cu is the main commodity, and 1055 showings (i.e. occurrences with Cu mineralogy but without any resource indication). Only five deposit types, however, are enriched with copper (igneous intermediate, VMS, mafic-ultramafic, sandstone- and shale-hosted and IOCG).

Geological formations favourable to copper are quite numerous and include essentially sedimentary and volcanic rocks (Fig. 2.6c). Ages are also widespread, with (i) Palaeoproterozoïc VMS, mafic-ultramafic type and IOCG in Scandinavia, (ii) Lower Palaeozoic Caledonian VMS and veins, (iii) Upper Palaeozoic VMS in the southern Iberian province and French Brittany, and (iv) Permian sandstone-hosted deposits and Cenozoic igneous intermediate porphyry deposits in the Balkan-Carpathian region.

The distribution of favourable areas clearly highlights the major known copper districts. In addition, because of the large dataset used (1777 deposits), a considerable amount of detail is present in the results and show favourable areas where copper mineralization has not been recognised, especially in the Balkan-Carpathian region.

2.5.2 Predictive Mapping for By-Product Commodities Using the Database Querying Method

2.5.2.1 Methodology

The objective here was not to discover new deposits but to evaluate know deposits for a new targeted commodity. When searching for 'high-tech' commodities, which most of the time are by-products, searching for a specific type of deposit (e.g. Cu–Mo porphyries for Re, or Pb–Zn deposits for Ge) does not help because it can contain, or not, the searched by-product. For several reasons (e.g. commodity not searched or not analysed), ore deposits mined in ancient times may have an unknown potential. Sampling the dumps and the tailings and then performing analyses could be a very costly task due to the generally complex structure of the mining wastes. Hence, the idea of a predictive method to assess the favourability for by-products of other commodities from deposits in the ProMine MD database. This was done by ranking deposits of the appropriate types in the database according to their similarity to deposits known to contain the targeted commodity. Interestingly, this non-spatial method, when applied to a number of deposits sufficiently important, may result, using a simple parameter of transformation (here the "enrichment ratio", see below), in the definition of favourable areas for the searched by-product.

After identifying the most favourable deposit types, those enriched in the target commodity, commodity associations were investigated in all deposits containing the target commodity in order to identify the most favourable polymetallic associations (or signatures). These signatures were then searched for, and the results ranked, in all other deposits to identify those favourable for the target commodity. The following steps describe the methodology in more detail:

Step 1: The frequency of the target commodity is evaluated by deposit type. This is then compared to the whole database and an "enrichment ratio" (ER) is calculated as follows:

ER = (frequency of targeted commodity in the deposit type)/(frequency of the targeted commodity in all deposit types)

($ER > 1$ for enriched types, $ER = 1$ for neutral types and $ER < 1$ for depleted types)

The ER is used to identify those deposit types most favourable for the target commodity.

Step 2: In all deposits that contain the targeted commodity and for each favourable deposit type, a list of associated commodities and their frequency is calculated. For a given commodity, the result is a table of characteristic polymetallic association, or "signature", associated with the presence of the target commodity in each favourable deposit type. This characteristic polymetallic signature is then searched for in all deposits of a given type.

Step 3: The deposits in the database are ranked relative to the polymetallic signature of the deposit type they belong to. The ranking is the sum, for all commodities in the polymetallic association, of the product of a

Boolean value (i.e. "commodity is present" = 1 and "commodity is not present" = 0) and the frequency of the commodity in the signature. This formula is applied to all deposits in the database that belong to enriched types (ER > 0) in order to measure their level of similarity to deposits containing the target commodity. The result is a score given to all ranked deposits, with higher values corresponding to greater similarity to deposits containing the target commodity. Deposits with a high score are more likely to contain the target commodity and should be investigated as a priority.

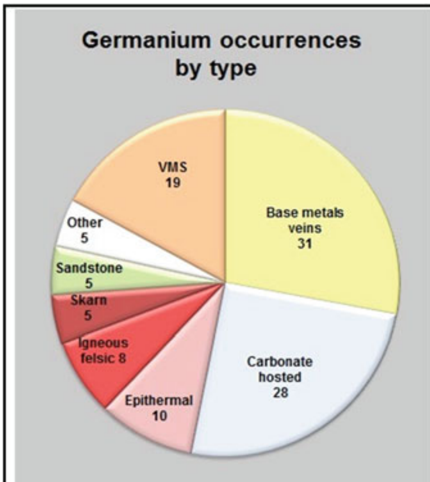
The results of ranking by deposit type can be displayed on a map using a rank-based symbology or iso-contouring. More globally, to display in a single map (and compare) results for a target commodity found in several types, the rank of each deposit is weighted by the ER (see step 1) of the type it belongs to. The results can then be mapped as density, in order to show the geographic distribution of favourability for the target commodity.

2.5.2.2 Predictive Maps for Selected Secondary or by-Product Commodities

Germanium

To measure the influence of deposit type on the presence of germanium (Höll et al. 2007), the enrichment ratio (ER) was calculated for each deposit type where germanium is present. This ratio is the frequency of germanium in the deposit type relative to the frequency of germanium in the whole database. Amongst the 7614 deposits that belong to one of the 16 commodity associations (or deposit types) defined by ProMine, 111 contain germanium. Germanium is preferentially enriched (i.e. high ER) in the following 4 deposit types (Table 2.6): carbonate-hosted (ER = 3.35), VMS (ER = 1.78), epithermal (ER = 1.50) and base metals veins (ER = 1.14). These 4 types include 79 % of the 111 deposits. The remaining 21 % are distributed in other types with lower enrichment ratios. The "base metals veins" type is only slightly enriched probably because it includes some parageneses (U, F, Co …) that are not favourable to the presence of germanium.

Table 2.6 Enrichment ratios (ER) of deposit types containing germanium



Metallogenic type	No. of occurrences	Enrichment ratio (ER)
Base metals veins	31	1.14
Carbonate-hosted	28	3.35
Epithermal	10	1.50
VMS	19	1.78
Igneous felsic	8	0.69
Igneousintermediate	1	0.59
Igneous replacement	5	0.98
Orogenic gold	1	0.20
Residual deposits	1	0.13
SandStone-and Shale-hosted	5	1.09
Sedimentary deposits	2	0.24

Table 2.7 Polymetallic signature of germanium-bearing deposits, by deposit type

Commodity	Global %	Base metals veins	Carbonate-hosted	Epithermal	VMS	Igneous felsic	Igneous replacement.	Shales- and sandstones-hosted
Zn	74	87	79	40	89	75	40	0
Pb	68	74	71	30	68	75	80	60
Ag	58	68	43	70	37	100	60	60
Cd	40	48	32	20	32	63	60	40
Cu	33	19	25	80	26	50	40	60
Ga	25	32	18	10	37	0	60	20
In	17	16	7	30	16	38	40	0
Au	15	3	4	70	11	13	40	40
Ba	12	13	14	20	11	13	0	0
As	11	13	11	30	0	13	0	20
Sb	10	6	7	30	5	13	40	0
Bi	9	6	4	10	5	13	60	20
Fe	8	0	7	10	16	0	40	0
Sn	7	10	0	0	5	38	0	0
Tl	7	3	4	10	0	13	40	20
Ni	6	3	7	10	5	0	20	0
Te	6	0	4	20	0	0	40	20
Co	5	3	4	0	11	0	0	20
U	5	6	0	0	0	25	20	0
F	4	10	4	0	0	0	0	0
Hg	4	0	7	20	0	0	0	0
Se	4	0	0	10	5	0	40	0

Considering only the deposits that contain germanium, the frequency of other associated commodities is calculated for each enriched type (Table 2.7). The results show, by deposit type, the commodities that are preferentially associated with germanium, or the characteristic polymetallic association. For instance, zinc, the most frequently occurring element, occurs in 87 % of base metals veins deposits that contain germanium, while Pb and Ag occur in 74 and 68 % respectively of these deposits. In epithermal deposits containing germanium, the polymetallic associations are quite different with Cu in 80 % of the deposits, but Zn in only 40 %. In this way a characteristic polymetallic signature associated with each favourable deposit type is established. This signature was then searched for in all deposits of a given type.

For each deposit in each identified favourable type, a rank was calculated in order to measure the level of similarity with deposits of the type that contain the targeted commodity (see step 3 here above). For instance, for germanium in base metals veins deposits, the ranking is calculated as follows:

Rank for base metals veins deposits = ((0.87 * [1 if Zn; 0 if not]) + (0.74 * [1 if Pb; 0 if not]) + (0.68 * [1 if Ag; 0 if not]) + (0.48 * [1 if Cd; 0 if not]) + (0.19 * [1 if Cu; 0 if not]) + (0.32 * [1 if Ga; 0 if not]) + (0.16 * [1 if In_; 0 if not]) + (0.03 * [1 if Au; 0 if not]) + (0.13 * [1 if Ba; 0 if not]) + (0.13 * [1 if As_; 0 if not]) + (0.06 * [1 if Sb; 0 if not]) + (0.06 * [1 if Bi; 0 if not]))

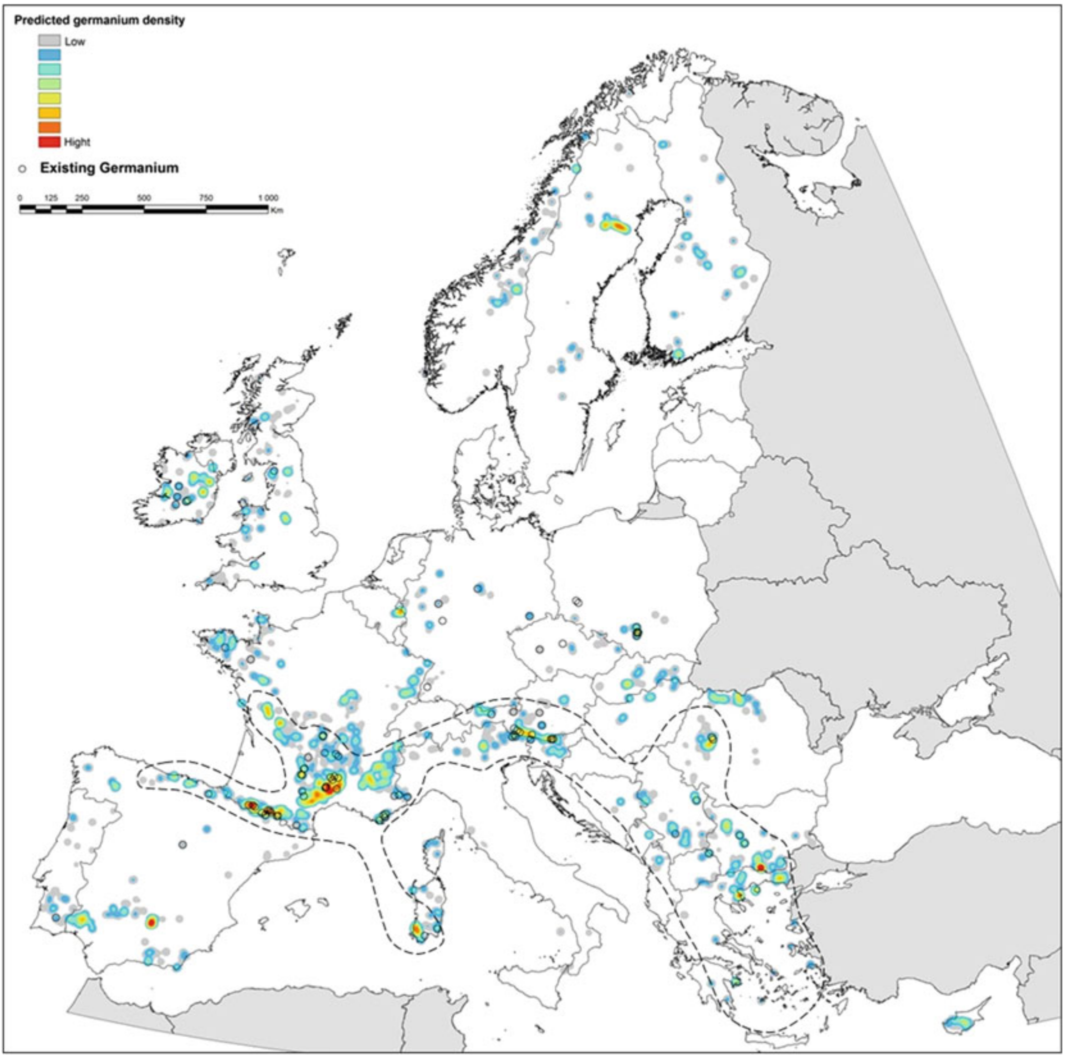


Fig. 2.7 Predictive map for germanium, obtained with the database querying method

The results for each favourable deposit type highlight those deposits that are most similar to those known to contain germanium and, consequently, have the highest probability of containing germanium. Then, to map and compare ranks of deposits from the different types, the ranking scores are weighted with the enrichment ratios (ER), as follows:

Global ranking = (1.14 * [1 if base metals veins; 0 if not]) + (3.35 * [1 if carbonate-hosted; 0 if not]) + (1.58 * [1 if epithermal; 0 if not]) + (1.78 * [1 if VMS; 0 if not])

The results are then mapped as density, in order to show the geographic distribution of areas favourable for germanium. The resulting map (Fig. 2.7) highlights a germanium province in southern Europe with various types of mineralization emplaced in the Lower Palaeozoic (Cambro-Ordovician), the Mesozoic (in relation to carbonates of the Tethyan margin), and the Upper Cretaceous-Cenozoic (porphyries and epithermal deposits). This temporal extension may be related to the palaeogeographic domain (Gondwana margin undergoing fragmentation during Cambro-Ordovician), distinct from the European terranes and where pre-concentrations had possibly occurred. Some areas, such as massive sulphides domains, also show relatively high favourability and should be investigated in more detail.

Gallium

Only 39 deposits in the ProMine MD database contain gallium. Five deposit types are significantly enriched in gallium (Table 2.8): igneous replacement (ER = 2.80), VMS (ER = 2.13), carbonate-hosted (ER = 2.04), epithermal (ER = 1.71) and base metals veins (ER = 1.26).

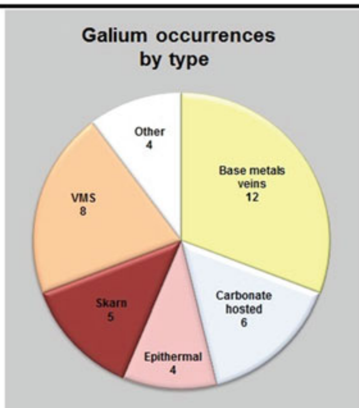
The similarity between polymetallic signatures (Zn, Pb, Ag, Cd) and enriched deposit types (base metal veins, carbonate-hosted, epithermal, VMS) for gallium (Table 2.9) and germanium (Table 2.7) is notable. Also, gallium-bearing deposits are commonly enriched in germanium (74 %) although the opposite is not necessarily true (25 %). It is also notable that in the "magmatic" deposit types (epithermal and igneous replacement) indium is often enriched along with Bi, Au, Sb and Te that are not present in other types.

After weighting of ranks by the enrichment ratio (ER) ((1.26 *base metals veins) + (2.04 *carbonate-hosted) + (1.71 *epithermal) + (2.13 *VMS) + (2.80 *igneous replacement)) the resulting map (Fig. 2.8) is very similar to germanium. However, the skarn domains are better depicted (e.g. Bergslagen district in central Sweden, the Pyrenees in France) as are the skarns and epithermal deposits in the eastern Europe districts (e.g. Moldova Nova in Romania, Majdanpek in Serbia, Trepča in Kosovo, Skouries in Greece).

Indium

Only 96 deposits in the ProMine MD database contain indium. Five deposit types are significantly enriched in indium (Table 2.10): igneous felsic (ER = 3.89), igneous intermediate (ER = 2.71), igneous replacement (ER = 2.5), epithermal (ER = 1.56) and VMS (ER = 1.3). Unlike germanium, indium (Schwarz-Schampera and Herzig 2002) is preferentially associated with "magmatic" deposit types (igneous and epithermals). Despite the fact that indium is

Table 2.8 Enrichment ratios (ER) of deposit types containing gallium



Metallogenic type	No. of occurrences	Enrichment ratio (ER)
Base metals veins	12	1.26
Carbonate-hosted	6	2.04
Epithermal	4	1.71
VMS	8	2.13
Igneous replacement (Skarn)	5	2.80
Pegmatite	1	0.63
Residual deposits	2	0.74
SandStone-and Shale-hosted	1	0.68

Table 2.9 Polymetallic signature of gallium-bearing deposits, by deposit type

Commodity	Global %	Base metals veins	Carbonate-hosted	Epithermal	Igneous replacement	VMS
Zn	83	83	50	100	80	100
Ge	74	83	83	25	60	88
Pb	74	67	67	100	100	63
Cd	69	67	33	100	100	63
Ag	63	75	17	100	100	38
Cu	26	25	33	25	40	13
In	26	8	0	75	80	13
Bi	23	0	17	50	80	13
Au	17	0	0	50	60	13
Sb	14	8	0	25	40	13
Te	11	0	17	25	40	0
As	9	17	17	0	0	0
Co	9	8	17	0	0	13
Ni	6	8	17	0	0	0
Ba	3	0	0	0	0	13
F	3	8	0	0	0	0
Mo	3	0	17	0	0	0
Sn	3	0	0	25	0	0
U	3	0	0	25	0	0
Y	3	0	0	25	0	0

found in 15 base metal vein deposits, this type is not favourable (ER = 0.64).

Polymetallic associations (Table 2.11) show that indium is typically associated with Cu and Sn, as well as Zn, Pb and Ag. Indium-bearing epithermal deposits are not associated with Sn enrichment, but are characterised by Ge and Ga in their polymetallic association. Presence of other commodities (e.g. W, Sb, Mo, Au) seem to be more controlled by the deposit type than the presence of indium.

As indium seems to be independent of other critical commodities, its distribution should be different. Indeed, the results (Fig. 2.9) for indium are very different to those of germanium and gallium. They highlight a vast domain (indium belt) that includes the tin province of Cornwall, UK, and Brittany, the north-western French Massif Central, the Vosges Mountains, the Erzgebirge in the Bohemian Massif and the north-western Iberian Peninsula. The results also show Cu- (and sometimes Sn-) rich VMS provinces such as Cyprus, the southern Iberian Peninsula, the Skellefte (Sweden), Vihanti-Pyhäsalmi and Outokumpu (Finland) districts, and Cu porphyry and epithermal domains in the Balkan-Carpathian region.

Tantalum

Only 93 deposits in the ProMine MD database contain tantalum. Three deposit types are significantly enriched in tantalum (Table 2.12): pegmatites (ER = 18.3), alkaline and peralkaline intrusions (ER = 12.21) and igneous felsic (ER = 1.95). Tantalum is most commonly associated with pegmatites (74 %) and their associated magmatic sources (alkaline-peralkaline and felsic magmatism). These associations are consistent with the incompatible behaviour of tantalum (Audion and Piantone 2012) that results

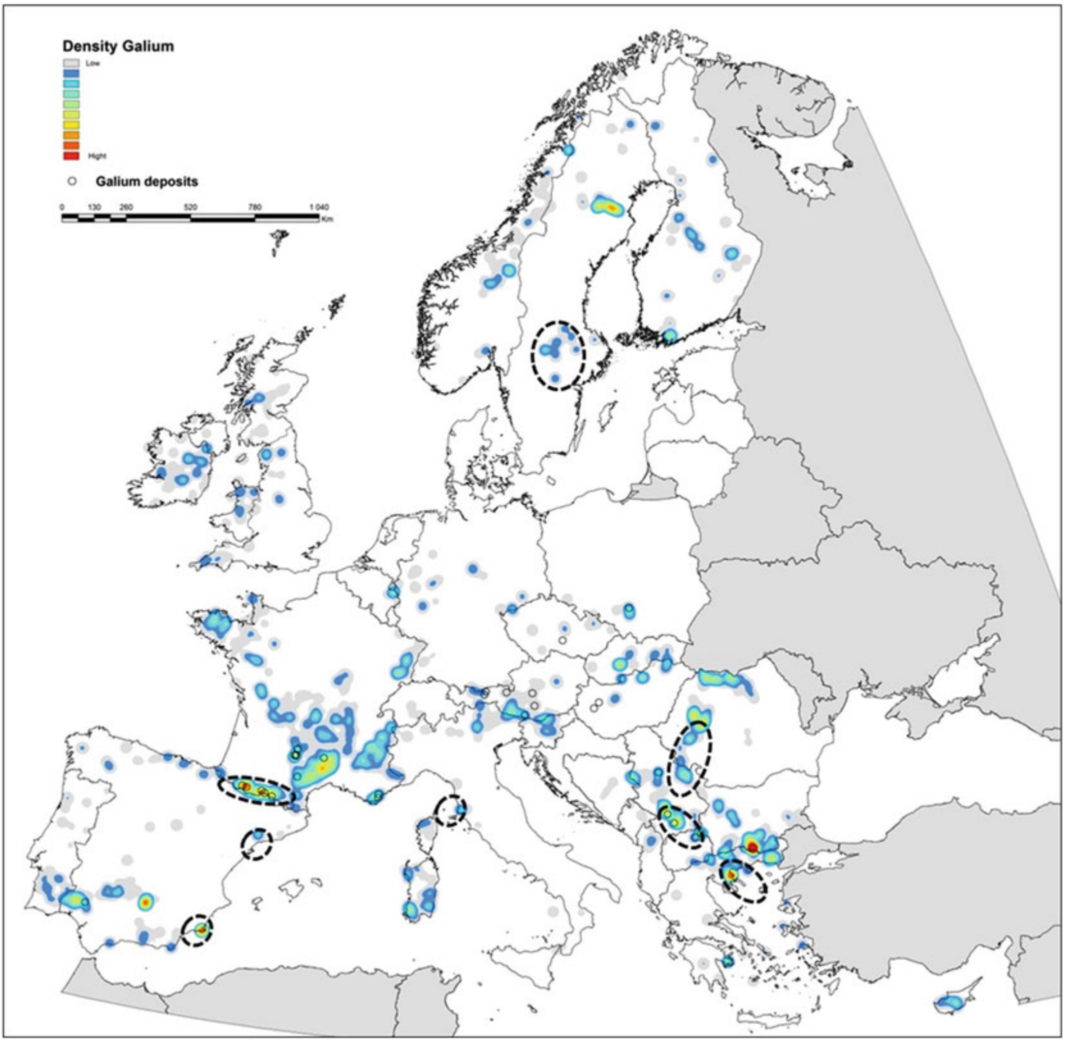


Fig. 2.8 Predictive map for gallium, obtained with the database querying method

in its concentration in highly differentiated residual magmas, in particular in pegmatites.

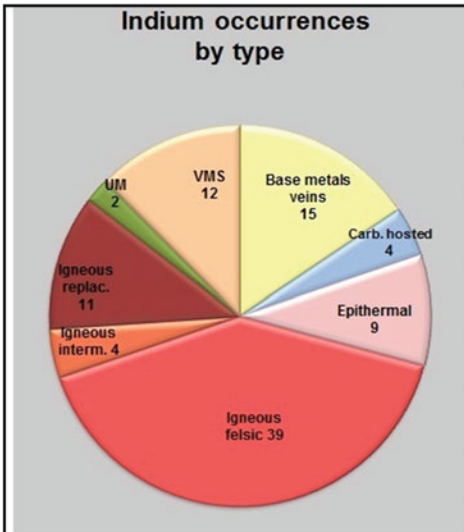
Tantalum-enriched deposits are characterized by a polymetallic signature (Table 2.13) with Be, Nb, REE and Li common in pegmatites. This signature also includes various other incompatible elements often associated with highly differentiated magmas (e.g. Beauvoir granite, in France, Cuney et al. 1992) such as Sn, U and Th. The presence of scandium, despite its low level, is unexpected and is difficult to explain.

The distribution of favourability for tantalum (Fig. 2.10) is similar to potential maps for the pegmatite deposits, the main Ta-bearing ore type. This distribution shows two main domains: (1) the Hercynian arc, related to crustal leucogranites magmatism, and (2) the southern Fennoscandian Shield, in the Sveconorwegian domain, and its associated magmatism.

Cobalt

A relatively large number of deposits, 239, in the ProMine MD database contain cobalt. Three

Table 2.10 Enrichment ratios (ER) of deposit types containing indium



Metallogenic type	No. of occurrences	Enrichment ratio (ER)
Epithermal	9	1.56
Igneous felsic	39	3.89
Igneous intermediate	4	2.71
Igneous replacement	11	2.5
VMS	12	1.3
Base metals veins	15	0.64
Carbonate-hosted	4	0.55
Mafic or UltraMafic	2	0.28

deposit types are significantly enriched in cobalt (Table 2.14): mafic/ultramafic (ER = 6.06), VMS (ER = 1.61) and residual deposits (ER = 1.10). The metallogeny of cobalt confirms that it is preferentially found in deposits related to mafic and ultramafic rocks and VMS. Less frequently, it can be present in residual deposits developed above ophiolitic basements and in some polymetallic veins. Cobalt can also occur in other deposit types, but generally without significant concentration. Cobalt is frequently associated with Cu and Ni, along with Zn, Au and Ag in VMS, or Cr and Mn in residual deposits (Table 2.15).

The most significant region (Fig. 2.11) is the Fennoscandian Shield, with important mineralization related to mafic and ultramafic complexes emplaced during the Palaeoproterozoic and the early stages of the Caledonian orogeny. In other regions of Europe, the favourability is more scattered and is related to mineralization of various types in the Cenozoic ophiolitic domain (especially lateritic nickel mineralization) to Bi–Co–Ni–Ag–U "five elements" veins (e.g. Bohemian Massif), and to VMS-type Cu mineralization, especially in Cyprus massive sulphides.

2.6 Data Dissemination and Web Portal

To disseminate ProMine data and results, an information system was developed. It is based on open and distributed architecture principles and the use of standards. The goal was not only to publish maps and data on a web portal, but also to allow these maps and data to be reused by other projects to make them interoperable. This requirement is in line with the European Directive INSPIRE[6] (Infrastructure for Spatial Information in Europe) which has specified rules to share information for 34 data themes, one of them being Mineral Resources. The INSPIRE principles can be summarized:

- the data and the layers must be described by their metadata (according to a standard) registered into a catalogue,

[6]Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE) http://inspire.jrc.ec.europa.eu.

Table 2.11 Polymetallic signature of indium-bearing deposits, by deposit type

Commodity	Global %	Igneous felsic	Igneous intermediate	Igneous replacement	Epithermal	VMS
Cu	56	49	75	64	78	83
Zn	66	56	25	91	44	67
Sn	46	74	75	36	0	17
Ag	46	26	50	64	78	50
Pb	47	21	25	73	44	58
Au	23	3	25	36	89	58
W	22	38	50	18	0	0
Cd	17	5	0	45	33	17
As	18	26	25	9	0	8
Mo	7	8	50	9	0	0
Li	6	10	50	0	0	0
Sb	9	3	25	27	11	8
Bi	15	8	0	36	11	25
U	16	15	25	9	11	0
Ge	19	8	0	18	33	25
Ga	9	0	0	36	33	8
Ba	10	3	25	9	0	8
Mn	5	3	25	9	0	8
F	8	3	25	9	0	0
Se	4	0	0	18	11	8
Tl	6	3	0	18	11	0
Co	4	3	0	0	0	8
Ni	4	3	0	0	0	8

- a view service must be setup to deliver the maps,
- an access (or download) service must be setup to provide the data,
- the data must be delivered according to a common, standard data model.

During the ProMine project, the following components were developed according to these principles:

- metadata have been provided for datasets and maps according to the ISO metadata standard (ISO 19115) and the INSPIRE profile (subset of the ISO standard);
- view services have been set up, compliant with the Web Map Service standard (WMS, specified by ISO and OGC, and selected for INSPIRE);
- an access service has been setup to deliver data according to the Web Feature Service (WFS, specified by ISO and OGC, and selected for INSPIRE);
- the Web Feature Service delivers data according to a standard data model, EarthResourceML (http://www.earthresourceml.org) developed by the IUGS/CGI (International Union of Geological Sciences / Commission for Geoscience Information, http://www.cgi-iugs.org/). To describe the geological aspects of mineral resources, the standard GeoSciML (http://www.geosciml.org/, also developed by the IUGS/CGI) has been used.

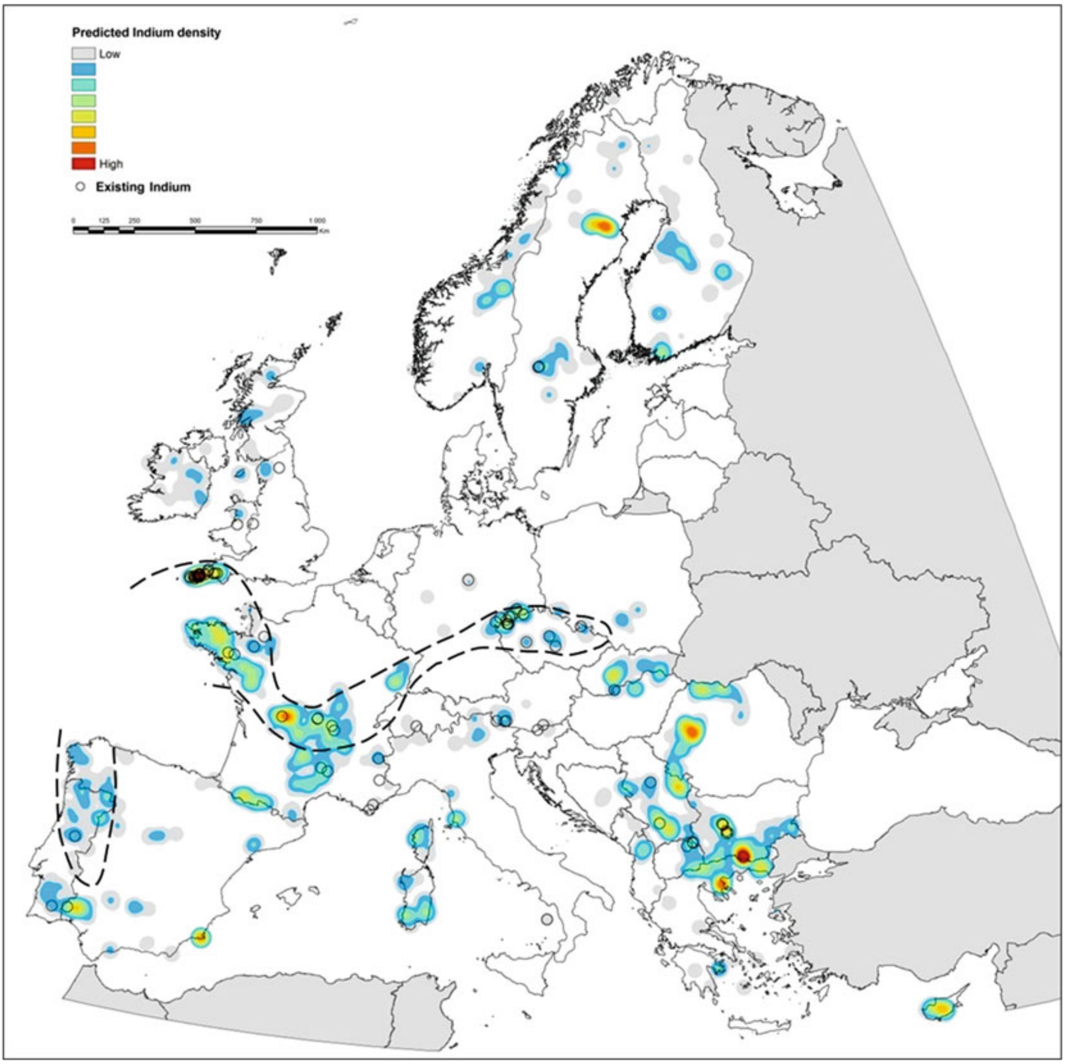
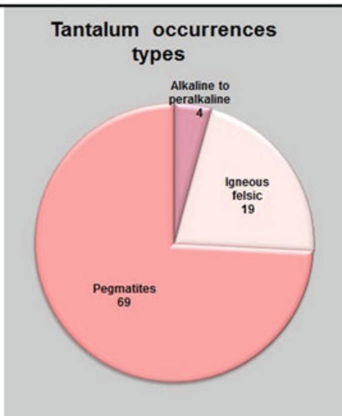


Fig. 2.9 Predictive map for indium, obtained with the database querying method, showing an “Indium belt” to the north of the Hercynian domain

All these elements are accessible from the ProMine internet portal (http://ptrarc.gtk.fi/promine) developed by GTK (Geological Survey of Finland). In addition, the clear separation between the ProMine portal and the web services make the maps reusable by other portals or applications. For example, the maps displaying the mineral deposits in the ProMine portal can be also displayed in the OneGeology portal (http://onegeology.brgm.fr/), using the ProMine WMS URL in the OneGeology portal.

It is important to note that for the ProMine databases to be fully compliant with INSPIRE and the distributed architecture principles, the data should have been managed and delivered by each data provider, and the European map should have been built by integrating all national maps. The INSPIRE principle related to this option states that the data should be managed at the “best” level, which is often the data provider. ProMine decided to implement a unique database for the following reasons:

Table 2.12 Enrichment ratios (ER) of deposit types containing tantalum



Metallogenic type	No. of occurrences	Enrichment ratio (ER)
Pegmatites	69	18.3
Alkaline to Peralkaline intrusions	4	12.21
Igneous felsic	20	1. 95
Igneous replacement	1	0.23

Table 2.13 Polymetallic signature of tantalum-bearing deposits, by deposit type

Commodity	Global %	Pegmatites	Alkaline and peralkaline	Igneous felsic	Igneous replacement
Be	44	46	50	37	0
Nb	44	42	75	47	0
REE	42	45	100	21	0
Li	34	30	50	47	0
Sn	31	23	0	68	0
U	26	19	75	42	0
Y	25	29	25	11	0
W	9	4	0	26	0
Sc	6	7	0	5	0
Th	4	4	25	0	0
Cs	3	3	0	5	0
Cu	3	0	0	11	100
Bi	2	3	0	0	0
Mo	2	1	0	5	0
F	1	1	0	0	0

- Not all the data providers were ProMine partners, so restricting data collection to ProMine partners would not have produced full European coverage;
- Not all partners had the capacity to setup web services according to OGC/INSPIRE rules to deliver their data compliant with the standard.

Nevertheless, the system is based on the use of standards and is able to manage more than one WMS. A possible next step for ProMine would be to split the central databases into a number of separate databases (one for each provider, i.e. by Geological Survey) and to ask the providers to setup a WMS and a WFS (the same as already

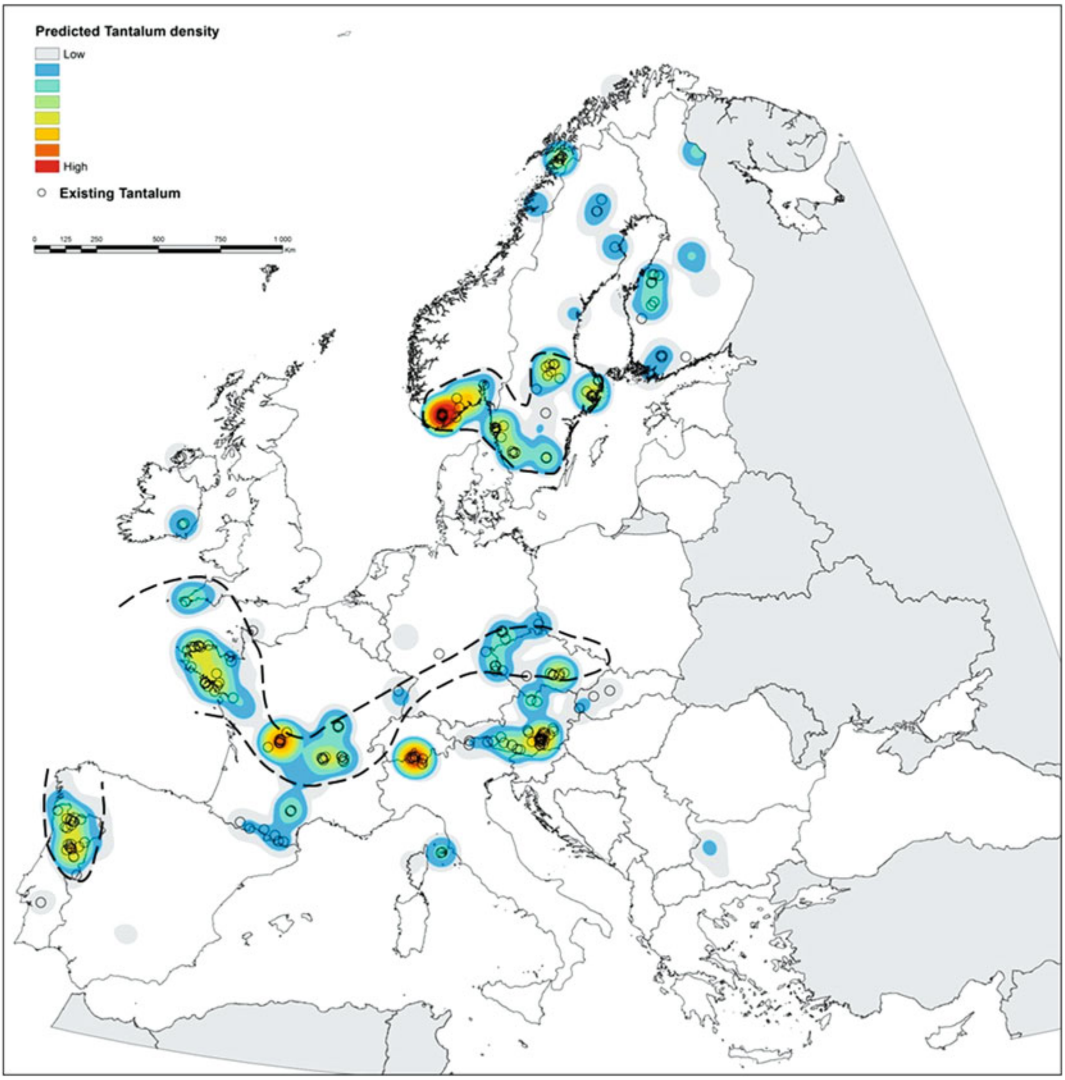


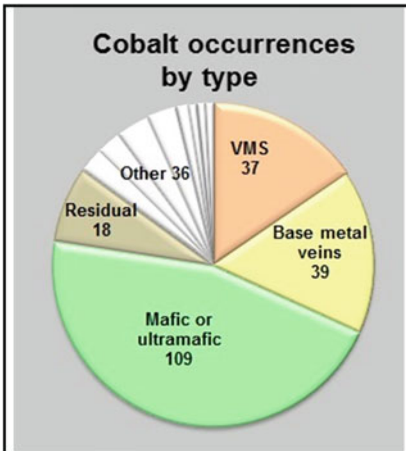
Fig. 2.10 Predictive map for tantalum, obtained with the database querying method

exists for ProMine, which would be facilitated by the use of open source software for the services).

By using real data the ProMine project has contributed to the improvement of the EarthResourceML standard and the INSPIRE rules to describe mineral resources, in terms of:

- Data model: the ProMine input is about Mining Waste, Mining Waste Measure and Exploration activity;
- Code-lists: many code-lists/vocabularies for EarthResourceML and INSPIRE have been improved from inputs by the ProMine project;
- Portrayal rules: no symbols were adopted in EarthResourceML and INSPIRE; ProMine has defined a set of symbols to display mineral deposits, mineral occurrences and anthropogenic concentrations which provide a starting point for the EarthResourceML working group.

Table 2.14 Enrichment ratios (ER) of deposit types containing cobalt



Metallogenic type	No. of occurrences	Enrichment ratio (ER)
Mafic or UltraMafic	109	6.06
VMS	37	1.61
Residual deposits	18	1.10
SandStone-and Shale-hosted	8	0.89
Base metals veins	39	0.67
Orogenic gold	6	0.56
Sedimentary deposits	7	0.39
Igneous felsic	6	0.24

Table 2.15 Polymetallic signature of cobalt-bearing deposits, by deposit type

Commodity	Global %	Mafic ultra mafic	VMS	Residual deposits	Base metals veins
Cu	0.87	0.86	0.84	0.11	0.90
Ni	0.83	0.94	0.49	0.94	0.38
Ag	0.19	0.09	0.46	0.06	0.28
Au	0.22	0.08	0.49	0.11	0.17
Zn	0.20	0.08	0.68	0.11	0.15
PGE	0.10	0.15	0.00	0.06	0.00
Pb	0.09	0.01	0.30	0.06	0.05
As	0.08	0.04	0.11	0.28	0.05
Cr	0.08	0.04	0.00	0.50	0.00
Mn	0.05	0.00	0.03	0.44	0.00
U	0.06	0.07	0.00	0.00	0.15
Bi	0.05	0.06	0.05	0.00	0.03
V	0.02	0.03	0.00	0.06	0.00
Ge	0.01	0.00	0.05	0.00	0.03
Sb	0.01	0.00	0.03	0.06	0.00

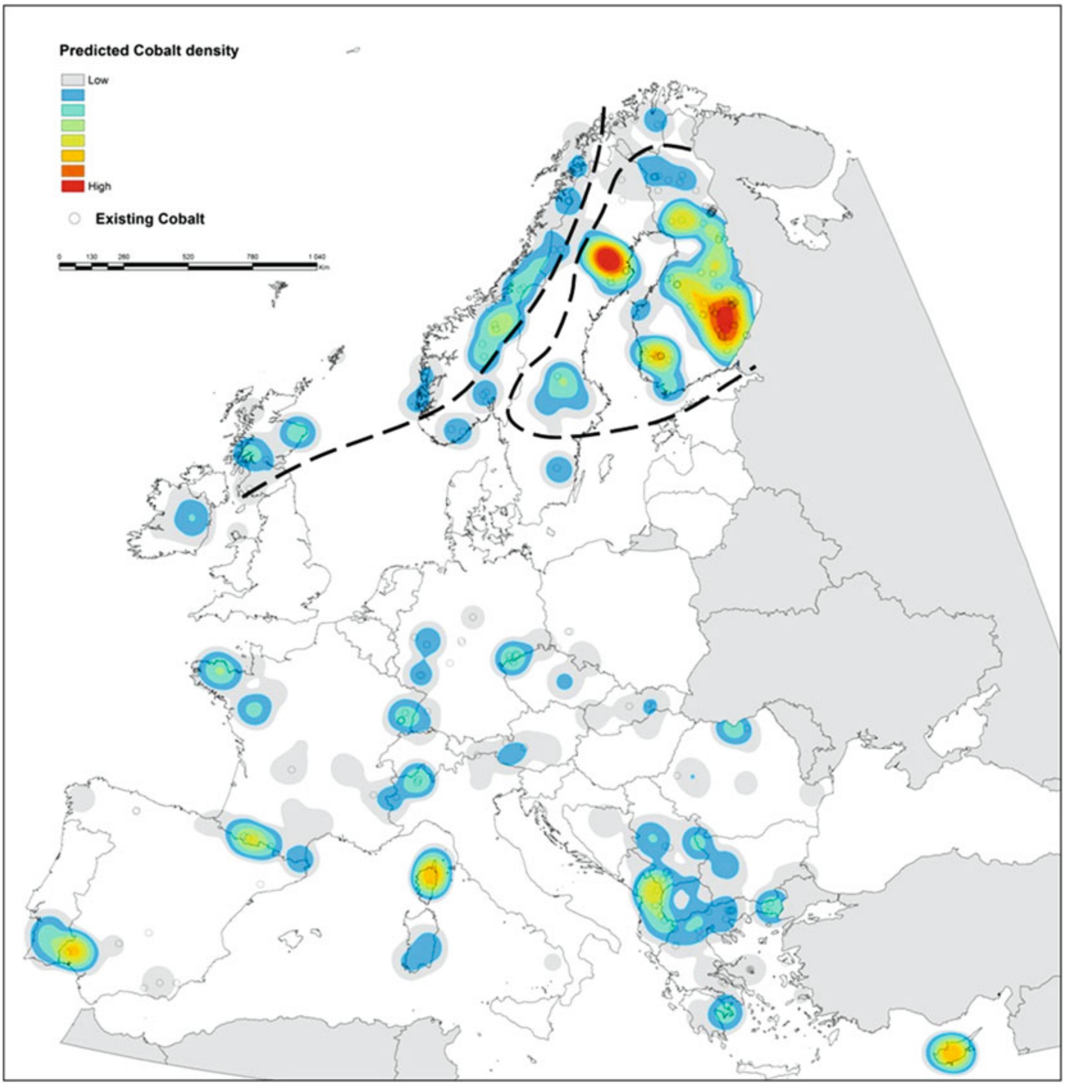


Fig. 2.11 Predictive map for cobalt, obtained with the database querying method

2.7 Conclusions

The ProMine databases described here are a significant deliverable from the ProMine project and a crucial step toward a better assessment of primary and secondary resources in Europe. This will strengthen the extractive industry and help secure the European supply of mineral resources, including critical and ‘green’ commodities. The MD database provides a new consistent and detailed dataset, containing a considerable amount of information that allows mineral resource potential and predictive assessment studies to be carried out. Preliminary assessments at the continental scale have been presented, but many other workers will be able to benefit from the ProMine MD dataset in the future for various purposes and at a variety of scales. The AC database is the first continental-scale dataset on mining and mineral processing wastes in Europe. It will need to be improved, by completing tonnages and grades data for instance, but already constitutes a crucial step towards a better assessment of secondary mineral resources in Europe.

Another significant output of ProMine WP1 is the development of a methodology that allows calculation of predictive maps for critical commodities. Classical methods (reviews in Carranza 2009b, 2011) are generally restricted to predicting major metallogenic types and their associated main commodities. Typical examples are gold-rich porphyries, Au-Ag epithermal deposits, etc. (see Billa et al. 2004 and Roy et al. 2006). The problem with critical commodities (e.g. Ge, Ga) is that they are rarely the main commodities in a deposit. They are most commonly found in the ores of a related commodity the presence or absence of which cannot be used to predict the possible presence of a deposit of the critical material. For instance, Cu–Mo porphyries may or may not contain Re. The presence of Mo is a prerequisite, but alone this is not sufficient. Similarly, Zn deposits may or may not contain Ge. The method developed for ProMine is strongly dependent on the quality of the descriptions entered in the database (description of all commodities contained in a deposit and of the mineralogy), their accuracy, their reliability and their completeness. The statistical approach adopted allows better characterization of the 'rules' governing the presence or the absence of the targeted commodity. By comparing exploited deposits for which the targeted commodity has never been investigated to those where it has been identified, the definition of possible new targets and prospective districts can be made.

The ProMine databases, together with the added-value layers derived from them (mineral potential and predictive maps) are publicly delivered through an internet web portal and web services. This ProMine portal complies with the most recent directives in terms of data visualization and delivery. It also provides a core knowledge base that will be very useful for new EU-FP7 and Horizon 2020 projects (e.g. EURARE, Minerals4EU).

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Appendix 1

Class Threshold Values for Selected Commodities

Commodity	Description	Class threshold values (in metric tons)			
		Super-large deposits (class A)	Large deposits (class B)	Medium deposits (class C)	Small deposits (class D)
Ag	Silver (metal)	10,000	2,500	500	100
Al	Aluminum (Bauxite ore)	1,000,000,000	100,000,000	10,000,000	1,000,000
Au	Gold (metal)	500	100	10	1
Be	Beryllium (BeO)	20,000	2,000	200	50
Bi	Bismuth (metal)	20,000	2,000	200	2
Brt	Barite ($BaSO_4$)	5,000,000	1,000,000	200,000	50,000
Cd	Cadmium (metal)	10,000	2,000	500	100
Co	Cobalt (metal)	500,000	50,000	2,000	200
Cr	Chrome (Cr_2O_3)	25,000,000	5,000,000	1,000,000	200,000
Cu	Copper (metal)	10,000,000	1,000,000	100,000	10,000
Fe	Iron (metal)	1,000,000,000	100,000,000	10,000,000	1,000,000
Fl	Fluorite (CaF_2)	5,000,000	1,000,000	200,000	50,000
Ga	Gallium (metal)	100	50	10	1
Ge	Germanium (metal)	500	100	20	5
Gr	Graphite (substance)	10,000,000	1,000,000	100,000	10,000
Hf	Hafnium (metal)	10,000	1,000	100	10
Hg	Mercury (metal)	50,000	5,000	500	100
In	Indium (metal)	500	100	25	5
Li	Lithium (Li_2O)	1,000,000	100,000	50,000	5,000
Mg	Magnesium, magnesite ($MgCO_3$)	100,000,000	10,000,000	1,000,000	100,000
Mn	Manganese (metal)	100,000,000	10,000,000	1,000,000	100,000
Mo	Molybdenum (metal)	500,000	100,000	5,000	1,000
Nb	Niobium–columbium (Nb_2O_5)	1,000,000	100,000	10,000	2,000
Ni	Nickel (metal)	2,000,000	500,000	20,000	2,000
PbZn	Lead + Zinc (metal)	10,000,000	1,000,000	100,000	10,000
Pltd	Platinoids, group (metal)	1,000	100	10	1
Rb	Rubidium (Rb_2O)	1,000	100	10	1
Re	Rhenium (metal)	5,000	500	50	5
REE	Rare Earths (RE_2O_3)	1,000,000	100,000	10,000	1,000
Sb	Antimony (metal)	100,000	25,000	2,000	1,000
Se	Selenium (substance)	5,000	1,000	250	50
Sn	Tin (metal)	200,000	25,000	1,000	100
Ta	Tantalum (Ta_2O_5)	25,000	2,000	1,000	200

(continued)

Commodity	Description	Class threshold values (in metric tons)			
		Super-large deposits (class A)	Large deposits (class B)	Medium deposits (class C)	Small deposits (class D)
Ti	Titanium, general (TiO_2)	20,000,000	2,000,000	200,000	20,000
V	Vanadium (metal)	2,000,000	200,000	20,000	2,000
W	Wolfram (WO_3)	200,000	50,000	5,000	500
Zr	Zirconium (ZrO_2)	1,000,000	100,000	10,000	1,000

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