

# EGS-relevant review of metallogenesis

## CHPM2030 Deliverable D1.1

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## CHPM2030 DELIVERABLE D1.1

# EGS-RELEVANT REVIEW OF METALLOGENESIS

*Summary:*

This document provides a review of metallogenic provinces in Europe. The ore-forming processes, the structure and the metal content of the ore deposits are discussed. Special focus is put on the mineral potential in the depth and temperature zones that are currently the target of EGS.

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## 1 Executive summary

In the provisioned CHPM technology an enhanced geothermal system would be established on a deep metal-bearing geological formation, which would be conducted in a way that the co-production of energy and metals could be possible. The aim of this study is to provide a metallogenic background for the potential development of this technology.

In the document the ore formation processes and the metallogenic provinces of Europe are reviewed, considering the relevancy with the EGS application, in order to identify the possible zones where the CHPM technology can be applied.

As the distribution of metallogenic provinces strongly correlates with the tectonic setting, four large metallogenic provinces can be identified within Europe: (1) Precambrian Fennoscandian Shield province, (2) Early Paleozoic Caledonian province, (3) Late Paleozoic Variscan province, (4) Mesozoic-Cenozoic Alpine province. The prospective zones or formations for the CHPM technology are assessed in each metallogenic province. Additionally to the mineralised intrusive bodies, thick sedimentary successions in extensional structures and deep-rooted regional fault zones can be also target areas both for the elevated heat flow and mineralisation potential from deep, fertile zones.

## 2 Introduction

### 2.1 Objectives and role of the CHPM2030 project

The strategic objective of the CHPM2030 project is to develop a novel technological solution (Combined Heat, Power and Metal extraction from ultra deep ore bodies), which will help reducing Europe's dependency on the import of metals and fossil fuels, and at the same time, lower the environmental impact of the energy supply.

In the envisioned technology, an Enhanced Geothermal System (EGS) is established on a metal-bearing geological formation, which will be manipulated in a way that the co-production of energy and metals will be possible. The project, at a laboratory scale, intends to prove the concept that the composition and structure of ore bodies have certain characteristics that could be used as an advantage when developing an EGS.

It is also planned to verify that metals can be leached from the ore bodies in high concentrations over a prolonged period of time and this may substantially increase the economics of the EGS. The project also aims to find proof for the concept that continuous leaching of metals will increase the performance of the system over time in a controlled way without having to use high-pressure reservoir stimulation. According to our expectations, this will provide new impetus to geothermal development in Europe. In the frame of the project, a Roadmap will also be developed to support the pilot implementation of CHPM systems before 2025, and full-scale commercial implementation before 2030.

### 2.2 Scope and structure of Work Package 1

The CHPM2030 project consists of nine work packages. Work package 1 – Methodology framework definition provides a conceptual framework for the technology of energy production and the extraction of metals from ore deposits located at depths below the conventional mining, where the temperature is above 100°C. Within this work package, we synthesise our knowledge of potential ultra deep metallic mineralisations in Europe that could be converted into an “orebody EGS”. The characteristics of these bodies and their implications for EGS will also be investigated. By working on the boundaries of geophysics, geochemistry, hydrogeology and geoenergetics we aim to discover and examine the geological, tectonic, geochemical, and petrologic factors that define the boundary conditions of such novel EGS both in terms of energy and potential for metal recovery.

Work package 1 consists of four tasks. Task 1.1 involves literature research and the summarisation of Europe's metallogeny from EGS-relevant aspects. Task 1.2 focuses on the extension of the current metallogenic models to greater depths, based mostly on our knowledge about the test areas, with a complete European outlook. Task 1.3 will investigate rock properties at laboratory conditions, and Task 1.4 will provide a synthesis of the outcomes of the former tasks within this work package.

### 2.3 Scope and role of Task 1.1

In the frame of Task 1.1 – EGS-relevant review of metallogenesis and ore deposit formation, we have investigated the mineral potential of Europe at the depths that are the target of the EGS systems. This is usually 4 km or more, but in favourable geothermal conditions it can be a shallower depth. The processes of ore formation and the metallogenic provinces of Europe have been reviewed, keeping an eye on the relevancy with the EGS application, in order to identify the possible zones where the CHPM technology can be applied. Special focus is given to the composition, geometry, extent, structure and textural characteristics of ore bodies, as well as the scale, pattern, and formation of the fracture systems.

## 3 Methodology

### 3.1 Role of this deliverable and relation to later work phases

This study is the first deliverable within Work package 1. It provides a synthesis of our understanding on the types of metallic mineral occurrences that exist at depths below conventional mining. The concept of the CHPM facility needs a suitable ore body located at great depths, where the ambient rock temperatures allow the development of a highly specialised Enhanced Geothermal System, which will be manipulated using novel geo-engineering approaches for maximum power output and the mobilisation of valuable metals.

Within this deliverable, Europe's deep mineral potential is examined, based on literature data. The geochemistry and structure of the different ore types are also discussed. It is important, because the methods to be developed in the project will target individual mineral formations taking advantage of their specific geochemical and structural features.

Beside the types of metals which potentially are enriched by the ore-forming processes, it is also crucial to understand the origin and structure of macro- and micro-fracture systems, which are characteristic for the given ore deposit. The natural fractures play an important role in controlling deep fluid circulation and heat extraction from deep geological formations. Our knowledge and understanding on the formation and nature of fracture patterns will be used as a base for the work in the later phases of the project. Both the metal content and the ore body structures will be taken into consideration during the laboratory experiments on the metal mobilisation (Work package 2) and the metal recovery (Work package 3).

### 3.2 Aims and structure of this document

The aim of the recent study is to provide a background, with the tools of ore geology and metallogeny, for formulating a detailed concept on the application of the CHPM technology in Europe. With the investigation of the metallogenic provinces and geothermal conditions of Europe, we can outline the areas where the CHPM systems can potentially be developed. The study is structured in eight sections:

In Section 1, we provide a short summary of this deliverable.

Section 2 is an introductory part. Here, the objectives of the CHPM2030 project are outlined, as well as the structure of Work package 1 and Task 1.1, within which the recent deliverable has been prepared.

In Section 3, the aim and the role of the recent document in the implementation of the project are defined and its relation to the other deliverables is described.

In Section 4, we provide a summary of the ore-forming geological processes and the mineral deposit types related to these processes. More details are given on those deposit types, which are relevant for the application of the CHPM technology, and the most important European examples are mentioned for each deposit type.

Section 5 is devoted to the metallogeny of Europe. We consider the main metallogenic provinces of the continent, with special focus on the four test areas which were defined in the proposal (South England, Iberian Pyrite Belt, Scandinavian Shield, and Romania). The EGS relevancy is discussed in each metallogenic province.

Section 6 is a synthesis of the outcomes of Section 5. Using a double screening, we merge metallogenic and heat flow distribution data in order to find the most favourable deep sites for developing CHPM projects.

Section 7 provides a list of references in which the bibliography used for preparing the recent study is listed.



## 4 Ore forming processes and ore deposits

### 4.1 Short review of ore forming processes

Metals are present in every rock forming the Earth's crust; each rock type has its characteristic chemical composition (Rudnick & Gao 2003). In spite of this, not all rocks can be used as sources of useful metals. Most important factors for this use are the concentration, the mineralogical-chemical form appropriate for technologies converting these into desired form for usage and the accessibility from the surface. The terms 'ore' and 'ore deposit' are used in several meanings in the geosciences (e.g. Bates & Jackson 1995, Robb 2005). In the CHPM2030 project, we consider ore as a rock material from which metallic components of economic value can be extracted, and ore deposit is any rock body from which this extraction is technologically possible via hot aqueous solution. In this context accessibility means mainly permeability of the host rock, and appropriate forms are those which can be readily solved by water and/or carbon dioxide without any chemical additives.

Ores can be formed either at the same time (syngenetically) with the magmatic, sedimentary or metamorphic host rock or during subsequent processes (epigenetically). Separation and enrichment of certain metals (or metalliferous minerals) is related to transport processes from a fertile source rock which becomes physically or chemically unstable to a zone of the host rock where the mineral phase incorporating the metals becomes stable. The transport medium is often an aqueous solution, but it may be rock melt or any fluid. Water can originate from the surface reservoirs (meteoric water), from the pores or from dehydration of water-containing minerals. Solution and precipitation is controlled by changes in temperature, pressure and chemical parameters of the fluid and its environment. The concentration of the ore elements in these solutions is rather low, deposits are formed on sites where the environment is stable enough to induce these changes during a geologically long enough time interval. Abrupt changes are usually bound to geological contacts. Pathways of the transport can be also controlled by lithologic boundaries, by porosity of rock bodies or by fracture zones (Evans 1993, Guilbert 2007).

The tendency of certain metals for mobilisation under given conditions depends on their geochemical character. Metals of similar character like lead and zinc, or niobium and tantalum tend to enrich or deplete together. However, some metals like iron have manifold characteristics and can participate in several element associations with minerals of variable stability properties (Dill 2010).

Considering all these factors, it is no surprise that the spatial distribution of ore deposits strongly correlates with the tectonic setting. Moreover, as several parameters like global heat flow, composition of the oceans and the atmosphere and configuration of the lithospheric plates changed through geological time, the temporal distribution is also uneven. In that sense, metallogenic provinces can be defined comprising tectonic units with rocks and ore deposits formed and altered in distinct time intervals by processes characteristic for the unit (Misra 2000, Dill 2010).

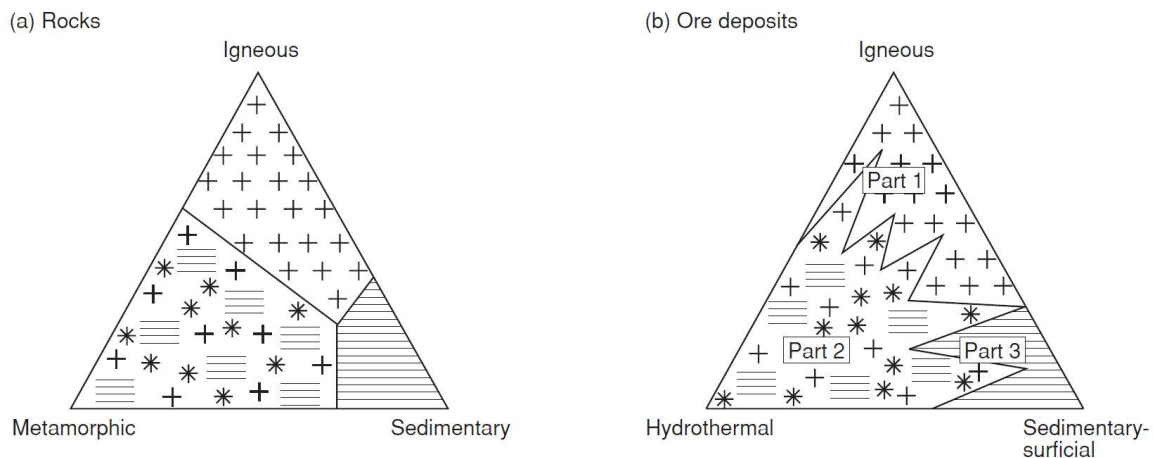
In the frame of the CHPM2030 project we concentrate on deposits which can be found in the depth required for the geothermal energy production and from which metals can be possibly mobilised in hot aqueous solution. Therefore we place less emphasis on near-surface chemical precipitations and placers, weathering products and supergene enrichments, as these occur mostly in shallow zones. Of course, in orogenic zones all of these can reach the necessary temperature zone, or even higher, having metamorphic overprints.

Syngenetic igneous ores and minerals of pegmatites are usually not capable of aqueous mobilisation, so these are also considered as not likely targets. However, in order to be complete, we shortly characterise all deposit types, but detailed introduction is restricted to processes involving transport in hydrothermal fluids.

## 4.2 Classification of ore forming processes and ore deposits

There are many different approaches and ways for the classification of forming processes and ore deposits. The primary classification is based on the potentially extractable metals, but the deposits can also be placed in a genetic framework based on the geological processes by which they are formed. In this study, we use this latter classification principle, and follow Robb's (2005) classification scheme.

Robb (2005) approaches the classification of ore deposits through the geological processes by which they are formed. He divides the processes (and deposits) into three main groups on a genetic basis: (1) igneous, (2) hydrothermal and (3) sedimentary processes and deposits (Figure 4.1).



**Figure 4.1** Classification of the main rock types (a) and an analogous, simplified classification of ore deposit types (Robb 2005)

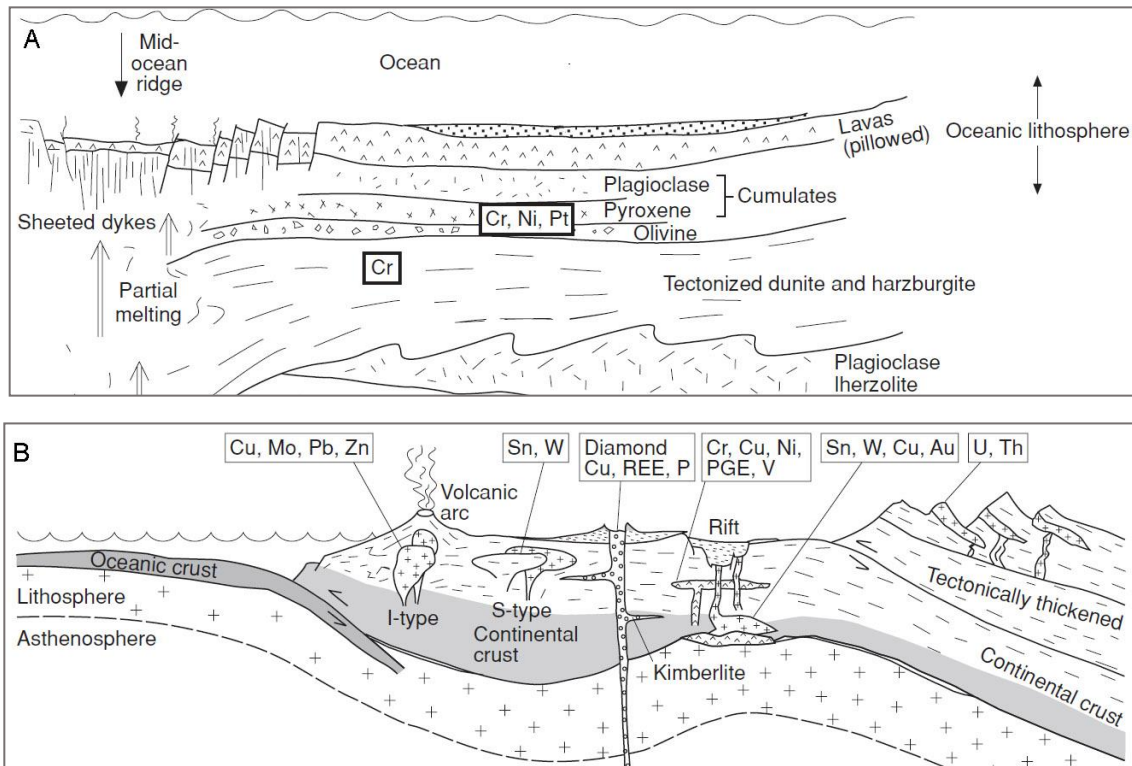
Between the three end-member categories there are “transitional” ones like magmatic-hydrothermal ore forming processes. In this case, the fluids which play a role in the transport and accumulation of metals originate directly from the magma. On the other hand, in the case of “pure” hydrothermal processes the mineralisations have no direct link to magmatism (although it can also serve as source of heat and some elements), and the fluid comes from pore water or metamorphic dehydration reactions. By making this division, we are aware that every deposit has a complex genesis with several additional processes. Thus, hydrothermal deposits often may have a precursor enrichment of igneous or sedimentary origin and, in turn, may have been overprinted by metamorphism or weathering.

According to the categories by Robb (2005), in the followings we provide a short characterisation of the following ore deposit types:

1. Deposits from igneous processes
2. Deposits from magmatic-hydrothermal processes
3. Deposits from hydrothermal processes
4. Deposits by surficial or supergene processes
5. Deposits from sedimentary processes

## 4.3 Deposits from igneous processes

Ore genesis is strongly linked to the lithospheric architecture. In the oceanic crust, chromite related igneous deposits are characteristic. In the continental crust, the ore deposits of igneous origin have a larger variety (Figure 4.2).



**Figure 4.2** Oceanic (A) and continental (B) architectures with the main types of characteristic igneous related ore deposits (Robb 2005)

Igneous rocks with different composition have different trace element associations (trace element: present in a rock at concentrations lower than 0.1 wt%). Ultramafic and mafic (basaltic) rocks are generally associated with siderophile and chalcophile elements like Ni, Co, Pt, Pd and Au. Intermediate (andesitic) rocks are usually related to Cu, Pb, Zn, Au and Ag deposits, but they appear to have no metal specificity and are characterised by trace element abundances intermediate between those of basalt and granite or alkaline rocks. Felsic (rhyolitic) rocks can host the enrichment of lithophile elements (e.g. Li, Be, F, Sn, W, Zr, U and Th). Alkaline magmatic rocks can be associated with a wide range of ore-forming metals like Cu, Fe, P, Zr, Nb, REE, F, U, and Th (Whitney & Naldrett 1989).

Metal concentration in igneous processes can be connected to (a) partial melting, (b) crystal fractionation and (c) liquid immiscibility.

When partial melting starts, trace elements are distributed between the melt phase and solid residue. Those that prefer the solid are referred to as compatible (they are built in the crystal lattice of an existing mineral), while those which prefer to remain in the melt are called incompatible. Consequently, the enrichment of trace elements and potential ore formation can be linked to the residual magma during progressive crystallisation, like the Zaaiploats tin deposit in the Bushveld Complex (Coetzee & Twist 1989). However, with a few exceptions, partial melting and felsic magmas are generally not associated with economic ore deposits (Taylor & Strong 1988).

Crystal fractionation is characteristic for mafic magmas. There are many mafic intrusions that contain layers of almost monomineralic chromite or magnetite (with titanium and vanadium). These layers are 0.5–1 meter thick and extend laterally for tens of kilometres. The most significant examples are the Bushveld Complex in South Africa and the Great Dyke in Zimbabwe. The formation of such layers, which are composed almost one single mineral (chromite or magnetite), is explained by fractional crystallisation, which means that the

normal crystallisation of silicate minerals temporarily stops and in a brief pause only the single oxide phase is formed (Irvine 1977).

The separation of crystal phases from residual melt is generally explained by gravitational segregation. Another mechanism by which crystal melt segregation can occur by filter pressing. The residual magma within a network of accumulating crystals in a partially solidified chamber can be pressed out into regions of lower pressure such as overlying non-crystalline magma or fractures in the country rock (Robb 2005).

Although the giant chromitite deposits form extended layers, chromitite can also appear in podiform structures. These structures are found in ophiolite complexes and form irregular, stratiform to discordant pods within dunitic and harzburgitic host rocks, which are often intensely deformed (Figure 4.2, A). The ore texture is built up by nodular and orbicular associations of chromite and olivine, which suggest that the mingling of two magmas has given rise to crystallization of the chromitite ores (Ballhaus 1998).

Liquid immiscibility is the segregation of two coexisting liquid fractions from an originally homogeneous magma. Silicate-sulphide immiscibility is related to mafic magmas and can lead to the formation of giant deposits such as the PGE sulfide deposits of the Merensky Reef in the Bushveld Complex, or the Ni–Cu sulphide ores at Sudbury in Ontario.

Sulphur is dissolved in the magma as sulphides displacing oxygen bonded to ferrous ions. Sulphide solubility varies as the magma progressively crystallises and, at the point when saturation is reached, small immiscible globules of sulphide melt will form. Segregated sulfide melts have a large potential to host large concentrations of chalcophile and siderophile metals, such as base metals (Cu, Ni, Co) and precious (Au, Pt) metal ores (Skinner & Peck 1969).

Except the podiform chromite ores in *Finland* and *Turkey*, the other igneous related ore types are not represented in mainland Europe. The chromites are not considered as viable targets for CHPM owing to their highly refractory nature to chemical attack. They can provide however good nickel values, since one of the host minerals, pyrrhotite, is relatively unstable, and may be dissolved more easily at depth.

#### 4.4 Deposits from magmatic-hydrothermal ore forming processes

Magmatic-hydrothermal processes cover transport and precipitation from juvenile water emitted from the melt, including metasomatism at the contact of intrusive bodies and their country rocks.

Water content of the magma comes from the molten minerals. Not only weathering products or rocks formed on the surface may contain water. Typical water bearing rock forming minerals also in igneous and metamorphic rocks are chlorite, clay minerals, serpentine and amphiboles. In arc related volcanism the subducting slab consists of hydrated ocean floor basalts and sediments providing much more water than mantle derived material of hot spots or spreading zones. Felsic (granitic) magmas are wetter than mafic (basaltic) magmas in general (Evans 1993).

The exsolution process of an aqueous liquid from magma was studied experimentally. The ongoing crystallisation will increase the water saturation of the remaining liquid phase. On shallow (1-2 km deep) levels this starts under decreasing pressure with relatively low crystallisation grade, so low density gas bubbles are formed in the melt comprising vapor of water and other volatiles, moving upward. This is called first boiling. On deep levels (2-5 km) the crystallization of water-free minerals must reach a higher grade (80–90%) for the sufficient saturation without change of the pressure, which is called second boiling. Of course, temperature, grade of crystallisation necessary to boiling and composition of the phases depend on the initial water content.

Boiling is important because it means a rapid separation of volatile phases and remaining magma mush. It can lead directly to precipitation of ore minerals along the paths of the upward moving fluids. Most of the halogenide, carbon-dioxide and sulfur content of the magma, light metals like lithium or beryllium and incompatible elements fractionate into the volatile phases. Elements which are chalcophile also tend to exsolve forming complexes with halogenides and other anions. Precipitation is controlled by cooling, decreasing of pressure and mixing with meteoric waters (Robb 2005).

#### 4.4.1 Pegmatite deposits

Pegmatites are very coarse-grained rocks derived from magma that may have crystallized in the presence of a magmatic aqueous fluid. They are typically associated with granites and comprise the major granite rock-forming minerals (Evans 1993). They also contain a wide variety of minerals with semi-precious character, such as tourmaline, topaz, and beryl. Pegmatites are also associated with relatively large concentrations of strategic lithophile elements, like Sn, W, U, Th, Li, Be, B, Ta, Nb, Cs, Ce, and Zr (Linnen et al. 2012).

Pegmatites can form in the depth interval 1.5-11 km. The shape of pegmatitic bodies varies greatly. It can range from pegmatitic schlieren and patches in parent granites, through thick dykes many kilometres long and wholly divorced in space from any possible parent intrusion. They can form simple to complicated fracture-filling bodies in competent country rocks, or ellipsoidal, lenticular, turnip-shaped or amoeboid forms in incompetent hosts (Evans, 1993).

The origin of pegmatites was explained by Jahns and Burnham (1969) as products of extreme crystal fractionation of mainly granitic magmas. They suggested that the transition from granite to pegmatite marked the point at which H<sub>2</sub>O fluid saturation occurred in the crystallization sequence and pegmatites, therefore, formed in the presence of an immiscible H<sub>2</sub>O + volatile fraction. The most giant pegmatitic deposits are Bancroft in Ontario, Canada, the Rössing uranium deposit in Namibia and the Bikita pegmatite in Zimbabwe.

In Europe, there are several less significant pegmatite deposits, but they are not considered as targets in the CHPM2030 project because in general, minerals are not capable of aqueous mobilisation.

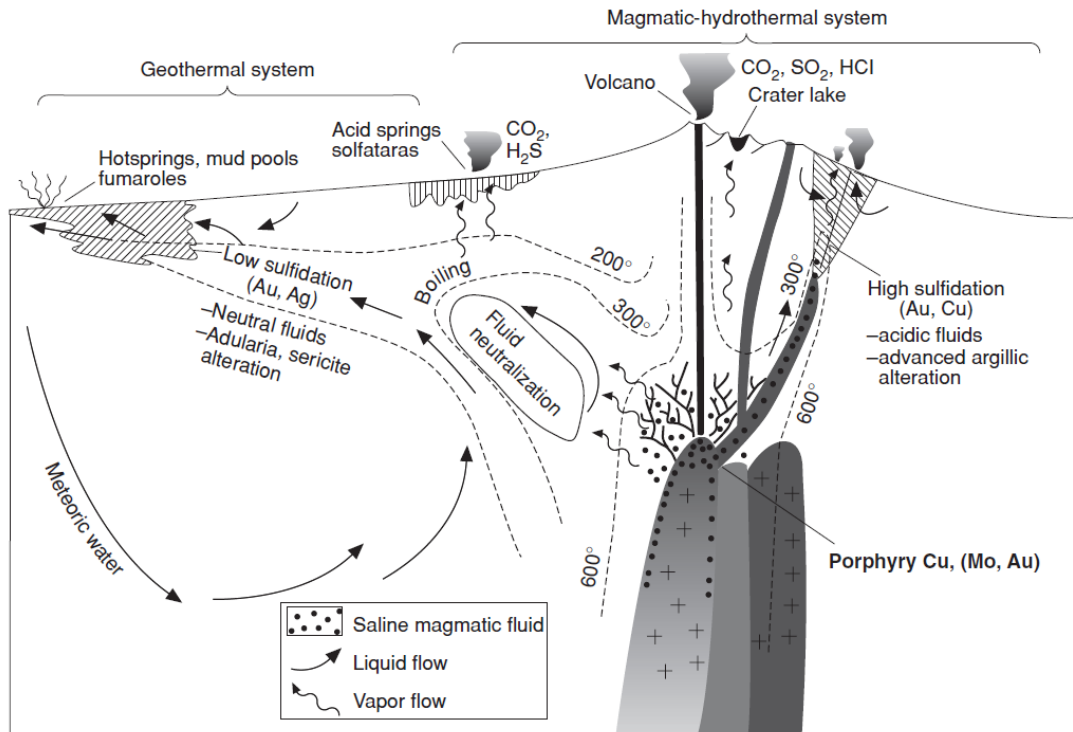
#### 4.4.2 Greisens deposits

Greisenisation is a rock alteration specific to the cupola zones of granites that contain Sn and W mineralisation, as well as significant concentrations of other incompatible elements such as F, Li, and B. It is a granoblastic alteration mineral assemblage comprising quartz, muscovite (or lepidolite), topaz, tourmaline and fluorite, usually adjacent to quartz–cassiterite–wolframite veins. The mineralisation occurs as large irregular, or sheet-like bodies immediately beneath the upper contact of late stage, geochemically altered granites and may extend downwards for some 10-100 m through a zone of albitisation into fresh granite (Reed 1982, Pollard et al. 1988). Greisens are frequently associated with pegmatitic and vein associated Sn, W and Li deposits.

In Europe, there are two world-class greisen deposits with historical mining activities: in *Erzgebirge*, Czech Republic–Germany and in *SW England*.

#### 4.4.3 Porphyry and epithermal deposits

Porphyry ore systems originate from the metasomatism by high temperature magmatic fluids exsolved from an intrusion. The typical texture in the name comes from disseminated sulphide crystals, but stockworks and veins are also common.



**Figure 4.3** Formation of porphyry Cu (Mo, Au) and epithermal Au, Ag, Cu deposits (Hedenquist et al. 2000)

Sulphides of Fe, Cu, Mo, Pb and Zn, native Au and W, Bi and Sn minerals are the most common ore components. The metasomatism extends usually uniformly to large volumes, reaching Mt or even Gt scale of reserves, but the ore grade is rather low (0.2–2 w% Cu, 0.01–0.5 w% Mo, ppb to few ppm Au; Pirajno 2009). Ore bodies are embedded in an alteration halo comprising fractured and brecciated rocks. Typical alteration processes of a porphyry system are propylitisation, hydrolysis (sericitic/phyllitic and argillic alteration), alkali exchange (potassic or sodic alteration) and silica addition (Seedorff et al. 2005, Pirajno 2009). Upward the mineralisation may show a transition to a high sulphidation epithermal system (Figure 4.3).

These systems are associated with the magmatism of intraoceanic or continental margin arcs, over subduction zones. The subducting slab, as pressure rapidly increases, loses water released from the metamorphism of hydrated mineral phases into dehydrated minerals. The peak metamorphism occurs at cca. 100 km depth. Together with the water, other volatile elements such as S, Cl, Na and K also penetrate into the mantle wedge of the overriding plate. This metasomatism induces a fluid-fluxed melting producing a magma enriched in chalcophile and siderophile elements, which can rise by buoyancy. Magmas of very wide compositional spectrum can develop. However, island arc magmas tend to be more mafic and enriched in Au, whereas voluminous felsic magmas of continental arcs are more often rich in Mo. Sn-W deposits are usually attached to S-type granite bodies.

The exsolved fluids penetrating the rocks overlying the magmatic intrusions are known from the inclusions. These are usually hypersaline over 750°C homogenisation temperatures and progressively decreasing in salinity with decreasing temperature. The mineralisations and alterations form concentric zones along and around the main pathways of the fluids. The zonation in the case of felsic magma was described as a model by Lowell and Guilbert (1970). The core of the alteration is surrounded by a potassic zone comprising mainly orthoclase (adularia), sericite, mica and Fe-Cu-Mo sulphides as ore minerals. In the phyllic zone quartz, sericite and pyrite are typical. In the argillic zone clay minerals and alunite are abundant with pyrite,

chalcopyrite and bornite. The outermost and widest (often several kms in diameter) is the propylitic zone with chlorite, epidot, calcite and pyrite.

In the case of mafic magmas the zonation pattern can differ from that. Phyllic and argillic zones may be absent. Potassic zone comprises mainly chlorite and biotite, the common ore minerals are chalcopyrite and magnetite. Propylitic zone may partly overprint the potassic alteration.

Epithermal systems start to develop where heating and convective circulation of pore water (either meteoric or sea water in origin) becomes dominant over magma-derived fluids. This is rather a near-surface process below 300°C in areas of enhanced heat flux, usually heated by a magmatic intrusion. The fluid pathways are controlled by faults, fracture systems or barriers of low permeability; lodes, vents and pipes are common ore bearing structures, although stockwork and dissemination is also possible. The water may reach the surface in form of hot springs. The mineralisation is leveled with changing metal composition. Sinters and subsurface precipitations of acidic, Cl-rich waters are enriched in Au, Ag, W, As, Sb, Hg and Tl. Cu, Te, Bi, then Pb and Zn concentrate in gangue assemblages of deeper levels of the system (Pirajno 2009).

Two basic types of mineralisation are typified (Simmons et al. 2005, Pirajno 2009). Acidic, S-rich solutions produce high sulphidation (HS) systems, often as a continuation of porphyry mineralisations. Gangue assemblage comprises vuggy and massive quartz, alunite, pyrophyllite, kaolinite and dickite. Pyrite, Cu-sulphides and sulphosalts (enargite, luzonite, covellite, tetrahedrite and tennantite), sphalerite and telluride minerals are typical ore minerals. Slightly alkaline solutions of lower salinity form low sulphidation (LS) systems, where the contribution of magma-derived fluids is minimal or missing. Gangue assemblage comprises quartz, chalcedony, adularia, illite, calcite and/or rhodochrosite. Electrum, acanthite, silver sulfosalts, silver selenides and Au-Ag tellurides contain precious metals, with sphalerite, galena and chalcopyrite as ore minerals.

The higher end of the epithermal range (deeper positioned in the volcanic systems towards subvolcanic levels) has been separated as intermediate sulphidation type (IS) by Sillitoe and Hedenquist (2003).

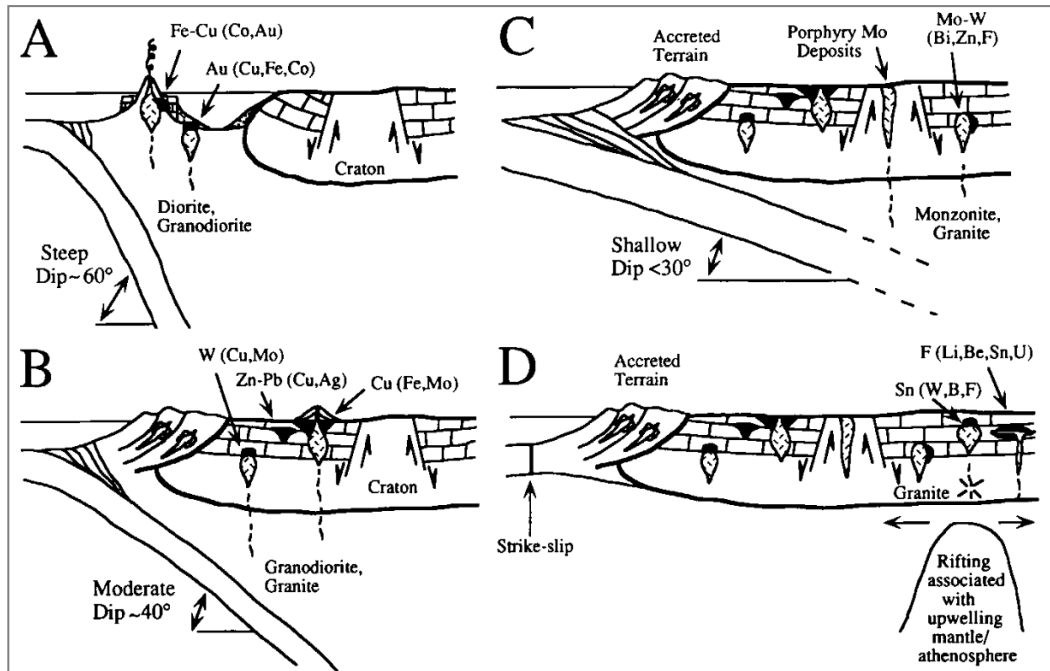
Central and Eastern Europe, a relatively young part of the continent in terms of geological times, are the home of large-size Phanerozoic volcanic-subvolcanic complexes, with world-class porphyry Cu-Au ores and in many cases with important epithermal Cu-Au-Ag mineralisation. Such deposits are known in Slovakia (*Banska Stiavnica, Kremnica, Biely Vrch*), Hungary (*Recsk*), Ukraine (*Muzhievo*), Romania (*Deva, Rosia Montana, Rosia Poieni, Moldova Noua*), Bulgaria (*Asarel, Medet, Chelopech*), Greece (*Skouries*) extending through Serbia, Macedonia, Turkey, with similar important active or inactive occurrences. Their age varies from Cretaceous to Pliocene.

#### 4.4.4 Skarn deposits

Skarn systems develop when the exsolved fluids get contacted with carbonate country rocks, forming calc-silicates as rock forming minerals. The mineralogy is complex and variable. Calcic skarns derived from limestone consist mostly of garnets, clinopyroxenes (diopside-hedenbergite series), wollastonite, scapolite, epidote and magnetite. Magnesian skarns derived from dolomite consists of diopside, forsterite, serpentine, magnetite, talc and also tremolite-actinolite group minerals when abundant silica is present. However, dolomitisation can occur also in limestone affected by skarn-forming metasomatism.

Tectonic setting and ore minerals can be the same as in the case of porphyry systems (in several cases these are in direct contact), but in rifting environments also Sn-W skarns can develop in contact with granitic plutons (Figure 4.4). Deep skarns (5-15 km) tend to be smaller than shallow ones, and these are mostly W skarns. Sulphide minerals tend to be more abundant in calcic than in magnesian skarns. Skarns have usually a

zonation controlled by decreasing temperature and salinity of the fluids migrating outward (Einaudi & Burt 1982). Ore (except Fe in magnetite) is generally restricted to the exoskarn. Dominant mineral groups of the exoskarns are from inside out: garnet, pyroxene, wollastonite and finally calcite (contact marble rocks). Massive sulphide replacements and veins occur mostly in distal skarn zone (Meinert et al. 2005).



**Figure 4.4** Tectonic models for skarn formation. A: oceanic subduction, B: continental subduction, C: transitional low-angle subduction, D: post-subduction or continental rifting (Meinert 1992)

A wide variety of metal associations can occur related to the skarn environment. These include W, Sn, Mo, Cu, Fe, Pb–Zn, and Au ores (Misra 2000). As a general trend, Fe and Au skarn deposits tend to be associated with mafic to intermediate intrusions. Cu, Pb, Zn, and W are linked to calc–alkaline granitic intrusions, and Mo and Sn with more differentiated granites (Robb 2005).

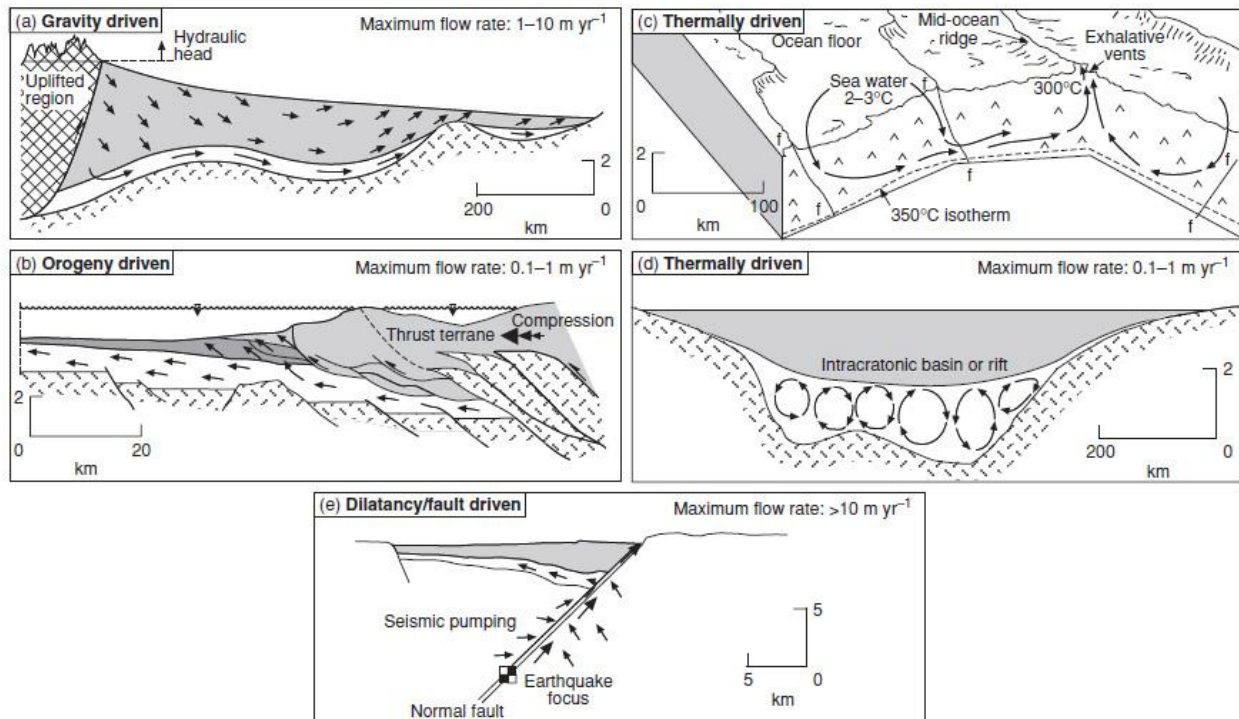
In Europe, significant skarn deposits can be found in the Carpathian Belt in Romania. Five of the seven major Romanian skarn deposits are located at the western end of the South Carpathians in the southwest *Romanian province of Banat*, and two are in the northern *Apuseni Mountains* (Nicolescu 2005).

#### 4.5 Deposits from hydrothermal ore forming processes

As opposed to the previous subchapter, in this group the meaning of the term ‘hydrothermal’ refers to any high-temperature water-based fluids circulating in the Earth crust, as vehicle of the metal transport, unrelated to known igneous sources.

The origin of water can be sea water, water derived from metamorphic dehydration, connate water and meteoric water. All these types may be mixed with brines of igneous origin. The origin can be traced by the stable isotopic ( $\delta D$  and  $\delta^{18}O$ ) composition ratio of the water. The elevated temperature needed for the dissolution and the stability of the metal bearing fluids is primarily derived from the internal heat of the Earth, as it is dictated by the geothermal gradient. This means, that the genesis of most deposit types in this group is related with depth, elevated temperature and increased pressure. Fluid movements in the Earth’s crust is controlled by the tectonic setting (Figure 4.5) (Robb 2005).





**Figure 4.5** Tectonic models for skarn formation (Robb 2005)

Both the chemical and physical character of the water participating in the process may cover wide ranges. The sea water in the global oceanic basins is well mixed, low salinity, low temperature fluid. This may play important role by its volume, salinity and convectonal subcrustal currents to mobilise metallic components from ocean floor sediments and rocks. Meteoric waters are low temperature, low salinity fluids, from atmospheric precipitation. As contrast, the connate water (i.e. the water filling the pore space of rocks) is more saline, generally high temperature fluid with significantly lower fluid flow velocities. It may be effective in producing anomalous metal concentrations in several geochemical barriers, like shales hosting copper, zinc, and lead enrichments. Finally, the metamorphic waters derive as expelled crystallization water from the mineral phase changes at the elevated pressures and temperatures deep in the Earth crust. They may be prime sources of significant ore deposits, like orogenic gold (Robb 2005, Pirajno 2009).

Besides temperature which is important controlling factor of ore precipitation, several others, like pressure, Eh, pH, and availability of complex ions also have a substantial role in the formation of hydrothermal ore deposits. Pure water is not an efficient solvent. Complexing anions, like chlorides, bisulfides, carbonate, etc. catalyse the uptake of metals by dissolution, ensure their mobility and make significant mass transport of metals in hydrothermal fluids possible. The mechanism of the fluid transport governs the metal enrichment in the fluids as well as the precipitation of metal bearing minerals in both macro and micro-scale. Understanding ore deposition therefore needs complex evaluation of the plate tectonic environments and investigating the fluid flow from pore to pore. Hydrothermal solutions are extremely dilute in chemical terms, large rock masses should be involved in the circulation system through geological periods (Pirajno 2009).

Among the parageneses produced by hydrothermal mineralisation, there are some which need special (e.g. highly alkaline) fluids; for example, metals enriched typically in pegmatites are improbable to be remobilized in this way. The usual metal enrichments in the waters and in the sinter deposits of some present-day hydrothermal systems should be taken into prime consideration (e.g. Christensen et al. 1983, Moore et al. 1983, Sanchez et al. 2015), when searching for recoverable elements by geothermal brines.

Mineralogy of the host rock or gangue minerals is important, as these minerals may also exchange ions with the solution or be solved and affect the composition of the solution, causing saturation at low concentration of useful ore metals.

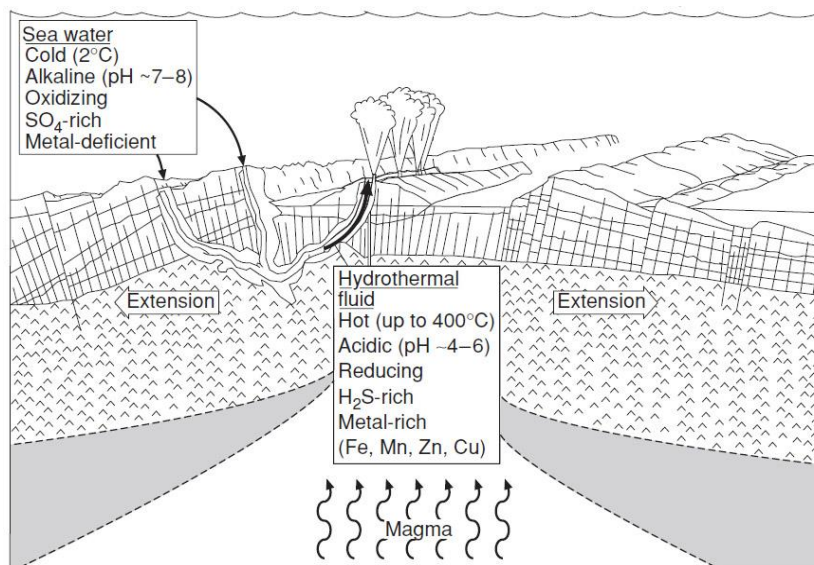
Most important ore controls are deep-rooted regional fault zones. In such environment the mineralisation processes producing the known exhumated and near-surface deposits are mostly unrelated to the lithology of the fault blocks or the vicinity of the zone. Deep veins are known from uplifted blocks of the basement (Dill 2010).

There is a large variety of deposit types under the “hydrothermal umbrella”. In the followings, the most important ones are discussed.

#### 4.5.1 Volcanogenic massive sulphide (VMS) deposits

With regard to the origin of the hydrothermal brines, the sea-water dominated submarine environment produces the volcanogenic massive sulphide (VMS) ore mineralisations. VMS deposits are also referred as VHMS deposits indicating that the mineralisation is hosted by volcanic rocks. The main metals of this environment are Cu and Zn (occasionally minor Pb and Au). The recent analogues for the VMS deposits are the black smokers, which are described as hot, metal charged, hydrothermal fluids that vent onto the sea floor, usually in zones of extension and active volcanism along mid-ocean ridges (Scott 1992) (Figure 4.5). The fluids originate from sea water, which circulates through the basaltic crust and, dissolves metals (Scott 1997). Black smoker fluids usually vent through tube-like structures, called chimneys that are built of a mixture of anhydrite, barite, and sulphide minerals such as pyrite, pyrrhotite, chalcopyrite, and sphalerite, as well as gangue opaline silica (Robb 2005).

One of the most important European VMS deposit group can be found in the *Fennoscandian Shield*. *Outokumpu* is a high grade Cu deposit containing minor Co, Ni and Zn. In the *Kohtalahti* deposit Ni is the dominant metal. *Pyhäsalmi* is the deepest ore mine in Europe, with Cu, Zn ores. The *Skellefte* district in Sweden (the Boliden polymetallic deposit as major occurrence) was once the richest Au-As deposit in Europe, and important Cu, Ag, Pb and Zn producer (De Vos et al. 2005).



**Figure 4.6** Fluid characteristics and circulation related to black smokers, recent analogues of VMS deposits (After Scott 1994)

Similar important zone is the 250 km long *Iberian Pyrite Belt*, stretching over Portugal and Spain. The Devonian-Carboniferous volcanic-sedimentary series hosts the largest concentration of massive sulphide deposits worldwide. About 90 VMS-type deposits are known. The most significant ones are *Rio Tinto* (Cu, Au), *Neves Corvo* (Cu, Sn) and *Aljustrel* (Cu, Pb, Zn, and Ag) (Inverno et al. 2015).

#### 4.5.2 Sedimentary exhalative (SEDEX) deposits

SEDEX deposits contain more than half of the world's known resources of Pb and Zn. They are typically formed within intracratonic rift basins and are hosted by organic-rich marine clastic or chemical sediments. The dominant metals are Zn and Pb (with minor Cu, but commonly Ba and Ag). It is generally agreed that mineralisations are the results of syn-sedimentary exhalative processes. Metal associations are related to hydrothermal fluids venting onto the sea floor, but without a direct link to volcanism (Goodfellow & Lydon 2007).

Although there is generally no spatial or temporal link between SEDEX and VMS deposits, several opinions state that they represent a continuum and are conceptually linked (Kirkham 1989, Misra 2000). The rift-related hydrothermal activity in the Red Sea is considered as a modern analogue for SEDEX deposits (Robb 2005).

The SEDEX deposits are well known in Europe. The largest important district of this type is the Irish metallogenic province. The most significant ore mineralisation is the *Navan* deposit, where *Tara Mine* is the largest underground zinc mine in Europe (De Vos et al. 2005).

In the *Harz Mountains*, Germany, the Devonian *Rammelsberg* and *Meggen* are similar deposits, with copper, silver, lead, zinc, barite as main metals. These two exhausted occurrences represent one of the oldest mining districts of Central Europe (Large and Welcher 1999).

#### 4.5.3 Orogenic gold deposits

Metamorphic dehydration of minerals is a form of water release at greater depths. With low temperature, low salinity solutions, near neutral pH, bisulphide complexes are dominant and may produce important ore types, called orogenic gold deposits (its earlier names are mesothermal vein associated, ancient gold-quartz and greenstone-belt gold). It relates to metamorphism, i.e. large scale plate collision, compressional forces, working as tectonics derived hydrothermal pumping system.

Although orogenic gold deposits are commonly associated with Archean granite-greenstone terranes, they are also hosted in Proterozoic and Phanerozoic settings. In orogenic gold deposits H<sub>2</sub>O-CO<sub>2</sub> phase separation is also considered to be an important process in gold deposition and may explain the rich accumulations of gold in quartz veins (Robb 2005).

The dominant and characteristic genetic features that link all orogenic gold deposits are a synchronicity with major accretionary or collisional orogenic episodes and the production of metamorphic – and in some cases magmatic – fluids that precipitate metals at various crustal levels along deep-seated shear and fracture zones. The main ore control is structural, along major shear zones or overthrusts (Bierlein et al. 2006).

In Europe, the *Karelian craton (Fennoscandian Shield)* hosts the most promising orogenic gold deposits along the Korvilanso-Kauravaara shear zone, with deposits of *Ilomantsi*, *Kelokorpi*, *Kuittila*, *Korvilanso* and *Ramapuro*. The zone has continuation towards Russia (Goldfarb et al. 2001). Similar deposits occur in Ukraine, in the southern part of Eastern Europe.

#### 4.5.4 Carlin-type ore deposits

A similarly important gold mineralisation but in dilatational tectonic regime is the Carlin-type sediment-hosted gold deposit. Earlier, these deposits were barely recognised, due to the unconventional host rocks (bituminous limestones and dolomites), and extremely fine gold grain size (around 2 micrometers). Lately promising exploration successes have led to discoveries and intensification of explorations of this ore type.

Fluids associated with Carlin deposits are similar to the metamorphic fluids in orogenic gold deposits. Gold deposition occurs where normal faults intersect a low-permeable cap rock, usually at a shale/limestone contact. The precipitation mechanism may be related to neutralization of the ore fluid during carbonate dissolution (Robb 2005).

Large et al. (2011) propose a two-stage basin-scale model for the mineralisation. In the first stage, gold and arsenic are introduced into black shale during the sedimentation. In the early diagenesis, in reduced settings, gold is partitioned in arsenian pyrite that grows in the muds. In the second stage, during late diagenesis and early metamorphism, the diagenetic arsenian pyrite is recrystallized to form coarser grained pyrite generations with “invisible gold”, and the organic matter is cooked to bitumen.

In Europe, occurrences were published from the *Rhodope Mountains*, in *Ada Tepe*, *Stremtsi*, *Rosino* (Marchev et al. 2003). Other large discoveries were achieved lately in *Korkan*, *Bigar Hill* in the *Timok Massif* in Serbia (Avalaresources Ltd. 2015).

#### 4.5.5 Quartz pebble conglomerate hosted gold deposits

Archean and Paleoproterozoic quartz pebble conglomerate hosted gold deposits contribute significantly to the world gold production. It has been dominated by the Witwatersrand conglomerate in South Africa. This deposit is also considered as a placer deposit but hydrothermal effects also played a role in gold enrichment.

The ore and associated minerals consist of native gold and pyrite, in most cases of detrital origin, and of the heavy minerals magnetite, uraninite, ilmenite and locally hematite. There is no general agreement on the origin of gold. Gold might have been introduced as detrital particles during sedimentation, or precipitated from hydrothermal solutions circulating through the sediments after sediment deposition. In both cases, metamorphism and associated metamorphic fluid circulation could be an additional component in the mineralisation (Robb 2005). In Europe, there is no example for this deposit type.

#### 4.5.6 Stratiform sediment hosted copper (SSC) deposits

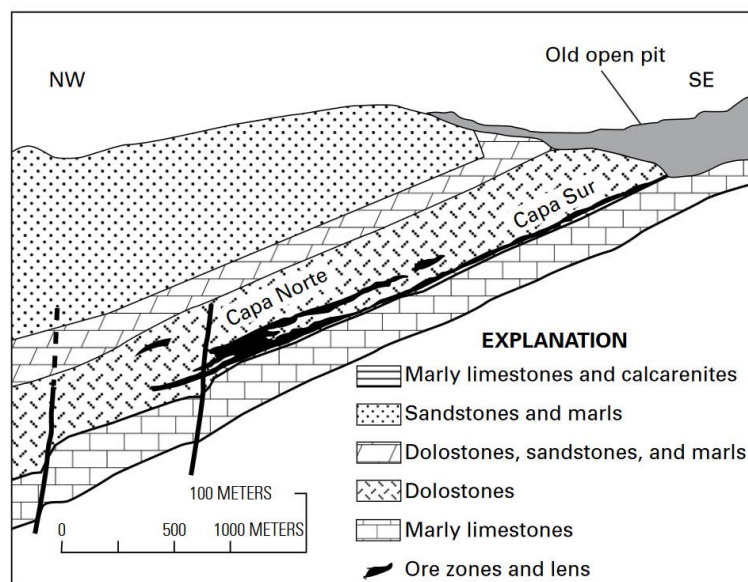
Connate water derived ore mineralisations may produce giant ore deposits in basin formations. In these deposit types metal transport and deposition is generally restricted to the sedimentary sequence through which the connate fluids circulate. This group involves the Cu-rich sediment hosted stratiform copper deposits (SSC, also called Red Bed Copper deposits) and the Mississippi Valley type (MVT) deposits, in which Pb–Zn ores occur.

SSC deposits comprise disseminated to veinlet Cu and Cu-Fe sulphides in siliciclastic or dolomitic sedimentary rocks. They are also significant sources of Co and Ag. SSC deposits are the products of evolving basin-scale fluid-flow systems. Metal sources are red-bed sedimentary rocks containing Fe oxy-hydroxides capable of weakly binding metals. Sulphur may be derived from marine or lacustrine evaporites, reduced seawater, or hydrogen sulphide-bearing petroleum. Metals are transported at low to moderate temperatures in moderately to highly saline aqueous fluids. Sulphide precipitation occurred due to reduction, typically caused by reaction with carbonaceous rocks or petroleum (Hitzman et al. 2005).

As a significant example for SCC deposits, the Permian *Kupferschiefer* is a major base metal district in Europe in *South-Western Poland*, and *South-Eastern Germany*. Stratigraphically it constitutes the boundary between the Lower Permian and the Zechstein (Upper Permian-Triassic) periods. Active mines reach a depth of 1200 m (De Vos et al. 2005).

#### 4.5.7 Mississippi Valley type (MVT) deposits

MVT ore deposits are Pb-Zn mineralisations hosted mainly by dolostone and limestone in platform carbonate sequences. They are usually located at flanks of basins, orogenic forelands, or foreland thrust belts. They have no spatial or temporal relation to igneous rocks. The ore fluid is also connate water, derived mainly from evaporated seawater and is driven within platform carbonates by large-scale tectonic events. MVT are generally stratabound but also can be structure controlled (Figure 4.6).



**Figure 4.7** Strata-bound and structure controlled MVT deposit. Cross section through the central part of the Reocin deposit, Spain (Leach et al 2010)

The main ore minerals are sphalerite, galena, and generally lesser amounts of iron sulphides. Silver is commonly an important commodity, and Cu is generally low (Leach et al 2010).

MVT and SEDEX deposits are similar in many aspects; both are sediment-hosted Pb-Zn mineralisations. The main difference is that SEDEX ores are syndepositional (or early diagenetic) with clastic-dominated host rock, while MVT deposits are epigenetic with carbonate host rock.

As a major MVT type mineralisation in Europe, the *Upper Silesian ore district* has been developed in flat-lying platform Triassic carbonate limestone and dolomite (De Vos et al. 2005).

#### 4.5.8 Sandstone hosted uranium-vanadium deposits

The near-surface meteoric water dominant systems are typical in terrestrial environments, in eolian or fluvial porous sediments. They generally do not produce significant primary ore deposits, with the notable exception of the sandstone hosted uranium-vanadium deposits. In oxidative environment, the  $U^{6+}$  forms stable complexes at near-neutral pH, and significant large tonnage low grade deposits can form.

Sandstone uranium deposits are widespread throughout Europe, dominantly of the Permian sandstones (*Novoveská Huta*, Slovakia; *Allier*, France; *Žirovski Vrh*, Slovenia; *Pécs*, Hungary), or Ordovician-Silurian shales

(*Gera-Ronneburg*, Germany). The deposits are related to sediments in which either syngenetic, or later diagenetic precipitations of uraninite occur in redox interfaces (IAEA 1985).

#### 4.5.9 Vein association deposits

Modern classification systems do not consider vein-type mineralisation as a genetic group, rather as a form of ore bodies. Many deposits which were formerly classified to this association have been identified as belonging to other ore deposit classes. However, in this study we characterise veins because they are important target mineralisations in CHPM systems.

Veins are generally formed by hydraulic fracturing and appear as tabular ore bodies extensive in two dimensions, often inclined as with faults. They are generally associated with plutonic intrusions. Most of the veins are formed from uprising hydrothermal solutions. A few veins are pegmatitic and represent end stage magmatic activity, and a few of them are volcanic sublimates. The thickness of veins varies from a few millimetres to a few metres (Evans 1993). Vein fillings can precipitate in a wide range of temperature. A characteristic feature of many hydrothermal vein deposits is the zoning of metals and minerals in space. Gangue minerals are dominant in vein fillings, among them quartz and calcite are the most common (Misra 2000). In the higher temperature hypothermal phase Sn and W are the most characteristic metals. At mesothermal temperatures Cu, Pb and Zn are dominant. In the epithermal phase the metal assemblage is shifted towards Au, Ag, Hg, Sb, Se, As and Bi (Lindgren 1933).

In Europe there are a large number of vein association deposits – although most of them are already not economically workable. The most significant ones are found in those complexes which were already mentioned at the greisens-type deposits: *South-West England* and *Erzgebirge* in Czech Republic and Germany.

## 4.6 Deposits from sedimentary processes

In this section we discuss deposit types in which the ore formation is related not only to sedimentary rocks, as it was in numerous examples with hydrothermal ores, but also to the sedimentation itself. Unlike the accumulation of the widespread common sediments (like sandstone, limestone, which can also be important raw materials) these sedimentation processes are somewhat special, and restricted to a small number of geological situations as well as geological periods. The accumulation of the useful components may be due to physical processes (like heavy mineral placers) or chemical sedimentation (black shales, evaporites, iron-manganese ores). The categories have overlaps in several points with the previously discussed igneous-related and other hydrothermal ore types, like SEDEX, or early diagenetic mineralisation from groundwaters, like the sandstone uranium deposits.

### 4.6.1 Lateritic and clay deposits, supergene enrichment

Laterites are the products of intense weathering in tropical regions, under humid and warm climate as residual sediments. They are economically important as they represent the main environment within which aluminum ores (bauxite) occur. They can also contain significant concentrations of Ni, Mn, Au, Cu and PGE (Wilson 1983).

Clay minerals are also produced by weathering and can form in-situ deposits or are transported and deposited in a sedimentary environment. Kaolinite is formed at humid conditions by acid hydrolysis of feldspar-bearing rocks. Illite forms under more alkaline conditions by weathering of feldspars and micas. The smectite clays commonly weather from intermediate to basic rocks under alkaline conditions (Wilson 1983).

Weathering can also result the supergene in-situ enrichment of certain metals like Cu, Zn, Ag and Au, in deposits which are situated on surface or near the surface. The process involves oxidation and hydrolysis of sulphide minerals. This enrichment is an important factor in the economic viability of low-grade ore mineralisations like porphyry copper deposits.

As these deposits form at continental surface or near-surface environments, they are not targets of the CHPM technology.

#### 4.6.2 Placer deposits

Placer deposits are clastic sediments in which high density (“heavy”) minerals are concentrated. The most common ore minerals in this deposit type are gold, uraninite, diamond, cassiterite, ilmenite, rutile, zircon and monazite. Placer deposits can form in alluvial, deltaic or beach environments. The Witwatersrand conglomerate, which was discussed in the previous section, is the most significant example for placer deposits (Heinrich 2015).

For the CHPM technology, the placer forming minerals are out of reach due to their outstanding physical and chemical stability, moreover, in Europe there are no significant placer deposits.

#### 4.6.3 Banded Iron Formations (BIF)

Banded Iron Formations are important types of the iron ores represented by giant deposits on cratonic areas. They have formed on passive continental margins, from Fe-enriched seawaters.

BIF ores are chemical sediments in which the major components, Fe and Si, were derived from the ocean. The metals have been transported to the seawater by hydrothermal exhalations (Isley & Abott 1999). They consist of alternating thin layers of iron oxides (hematite and magnetite) and silica. The formation mechanism of BIF ores is controversial as there are no recent analogues, these deposit types were formed only in the Archaean and Paleoproterozoic and in many cases they underwent metamorphism.

Although BIF deposits are important iron ores worldwidethere are no significant occurrences in the EU countries.

#### 4.6.4 Ironstone deposits

Ironstones (also referred as minette ores) are deposited in shallow marine environments and consist of goethite and hematite as oolites. The deposits contain little or no chert, but are associated with Fe-rich silicate minerals such as glauconite and chamosite. The iron was introduced from a continental source via a fluvial system in which iron was either in solution as  $Fe^{2+}$  or transported as a colloid. Microbial activity takes significant role in the concentric precipitation of the ooidic pellets. The main iron minerals can be very efficient absorbents to fix other metals on their surface. Nickel, cobalt and vanadium are known as important minor components of the minette ores (McGregor et al. 2010).

In Europe, the Jurassic minette ores in *France (Alsace-Lorraine)* and *Luxemburg* represent ironstones. They are more prone to a leaching process, due to their large carbonate content and oolitic texture, which may be easier to attack chemically, but also ending as an efficient residual proppant during the leaching in depth.

#### 4.6.5 Bedded manganese deposits

Bedded manganese deposits are close relatives to BIF iron ores, but with manganese dominance. Normally these are oxides (pyrolusite) or carbonates (rodochrosite), with rhythmic intercalations of iron-rich shale varieties (chamosite, nontronite, celadonite, glauconite etc). The deposits are formed in isolated anoxic or

euxinic basins, where Eh-pH conditions govern the alternating precipitation of Mn-rich or Fe-rich laminae. A recent analogue for the formation of sedimentary manganese ores is the Black Sea, where active sedimentation results in ongoing accumulation of  $\text{MnO}_2$  (Robb 2005). Apart from Mn and Fe, other important minor elements may be enriched in this ore type, like REE and cobalt.

The largest bedded manganese ore district is the South Ukrainian Oligocene Basin and its deposits include about 70% of the world's manganese ore reserves. It is a part of the vast South European Oligocene Basin, which contains the manganese deposits of *Chiatura* (Georgia), *Nicopol* (Ukraine) *Mangyshlak* (Kazakhstan) and *Varnentsi* (Bulgaria) (Evans 1993).

#### 4.6.6 Black shales

Although they are not considered as ore deposits, black shales can be important hosts for metal enrichments. They are fine grained argillic sediments, especially rich in organic matter (over 1% org C and lack of free oxygen). These sediments were formed in anoxic (or euxinic, where even  $\text{H}_2\text{S}$  is stable) environments. They may host anomalously high concentrations of V, Cr, Co, Ni, Ti, Cu, Pb, Zn, Mo, U, Ag, Sb, Tl, Se, and Cd. Black shales preserve their reducing lithology over geological time and may then act as epigenetic traps for redox-sensitive metals in a broad hydrothermal ore deposit spectrum (Lehmann 2014).

Globally, black shales are contemporaneous with the ironstones and genetically linked to the Ocean Anoxic Events (OAE), which are attributed to periodic oceanic highstands, in the Ordovician-Devonian and the Jurassic periods (Robb 2005).

In Europe, during the Cambrian, at the passive continental margin of Baltica, the bituminous and pyrite bearing, 20-60 m thick Alum Shale and its counterpart, kukkersite (in Estonia), were formed. The rocks are known for their widely distributed U, Mo, Ni, V, As, Zn, Cd and Pb enrichment (Lassen & Thybo 2012).



## 5 Metallogenic provinces of Europe

### 5.1 Principles of the division

Metallogeny is the study of the genesis of ore deposits, with emphasis on their relationships in space and time. The deposits are unevenly distributed geographically, so deposits of specific metals, or deposit types, or deposits formed in an epoch of the Earth history can form regional clusters: the metallogenic provinces. Of course, if a province was defined by a mineral association (e.g. Iberian Pyrite Belt), it does not mean the distribution area will not contain other kinds of deposits, or such deposits cannot occur in other parts of a larger region.

The genetic processes are related to tectonic environment (and heat flow, which is important for us as well is related), consequently, provinces are determined best by the tectonic units. Orogenic zones preserve products of complete tectonic cycles from rifting across opening and closure of oceanic basins ended in collision. Despite of its small size as a continent, Europe has a complex tectonics (e.g. Blundell et al. 1992, Plant et al. 2005): a current collision of the Eurasian and the African plate with several microplates between these, also subduction in the Mediterranean region, and sutures of several earlier plate margins (with convergent and divergent phase formations as well) support the variability. Known ore deposits of Europe are summarised (e.g. Dunning et al. 1979, 1982, 1986, De Vos et al. 2005, Pohl 2011, Ridge 2013a,b) and mapped (e.g. Juve 1998, Cassard et al. 2008) in several publications.

Tectonics is important also because required heat level for our ore deposits means in several regions the depth of concealed basement below allochthonous thrust units or volcano-sedimentary cover successions. Information gained by prospecting, exploration and mining of ores comes from shallow occurrences almost exclusively (except hydrocarbon exploration), and possible extrapolations to these unexplored depth levels depend on the tectonic model.

According to these features, four large provinces can be delineated covering the area of the EU: the Precambrian cratonic core of the continent (Fennoscandian Shield), the Early Paleozoic Caledonian Range, the Late Paleozoic Variscan (or Hercynian) and the Mesozoic-Cenozoic Alpine (or Tethyan) realm (Figure 5.1). As these orogenic zones and conjugated metallogenic processes are overlapping, this division doesn't mean the complete lack of Phanerozoic deposits on the shield or the absence of a mineralised and metamorphic 'Variscan' basement in the Alpine mountain chains. In the overview, however, provinces will be treated rather as geographically than as historically constricted units, so all mineralisations will be introduced according to its geographical position. A more detailed description is provided separately on four regions, which were chosen as preliminary project test areas.

### 5.2 Overview of the provinces

#### 5.2.1 Fennoscandian Shield province

##### Tectonics and mineralisations

The Precambrian processes and ores of this province were summarised by Weihed et al. (2005). The core of the continent in the Northeast is the **East European Craton** comprising Archean granitoids and greenstone belts. The Baltic Shield is denudated in the North, with hardly any deposits worth to mention, although diamond and orogenic gold explorations had some positive results. Voronezh and Ukrainian Shields are covered mostly by thick, undisturbed Phanerozoic sediments. Most typical deposits are ferruginous quartzites (BIF-type Fe deposits, e.g. *Krivoy Rog-Kremenchug Zone*). A belt of layered mafic intrusions records

a Paleoproterozoic (cca. 2.4 Ga) rifting event hosting Ni, Cr, Cu and PGE deposits, including the *Kemi* chromite as a major deposit (Alapieti et al. 1989). In the Lapland granulite belt Ti-Fe, Cu-Ni (*Lovno-ozero*) and Au-PGE mineralisations occur (Rundqvist & Sokolov 1993).

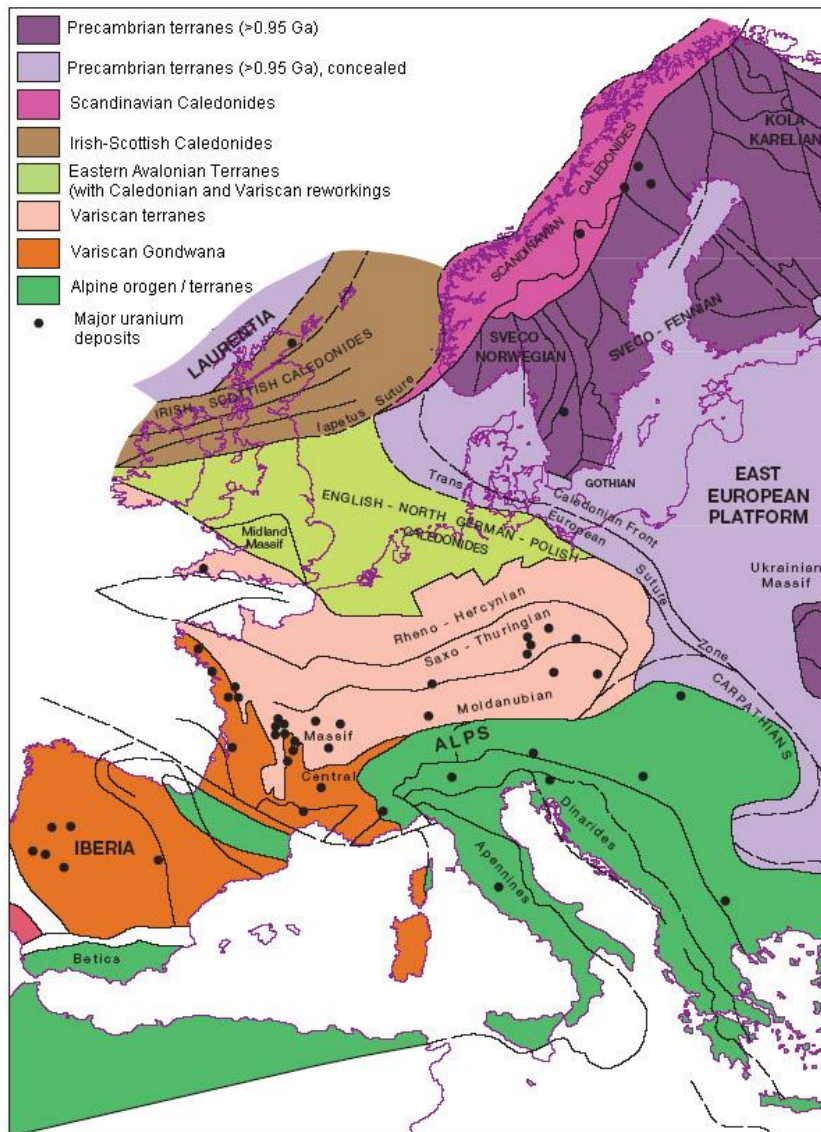


Figure 5.1 Major tectonic units of Europe (Plant et al. 2005)

A SE–NW border zone on the SW side of the Baltic Shield, the Proterozoic (2–1.7 Ga) *Svecokarelian* (or *Svecofennian*) **Orogenic Belt** is of considerably larger importance with world-class Fe, Ni and Cu deposits. It is the product of collision into the Columbia (or Nuna) supercontinent. Both island arc type and mid-ocean range type volcanics are present. In Northern Sweden, at *Kiruna* volcanogenic, stratiform, apatite bearing iron-oxide (magnetite and hematite) deposits are typical, hosted by alkaline, rifting-related volcanics. The steeply dipping ore bodies extend downwards cca. 2 km. The ore is enriched in REE and Y up 2–7000 ppm (Frietsch & Perdahl 1995), hosted partly by apatite and by accessory REE minerals (Pålsson et al. 2014). In the South, from *Skellefte* in Sweden, in the West across Finland (*Outukumpu*, *Pyhäsalmi*) to the *Lake Ladoga* in Russia in the East, polymetallic sulphide ores form important deposits. Cu, Zn, Pb, Co, Ni, Ag and Au are the most frequent enriched metals. The deposits often are attached to granitoid intrusions in a felsic volcanic country rock assemblage (*Boliden*), but also to ultramafic mantle peridotite rocks (*Outukumpu*, Peltonen et al. 2008). Late orogenic alkaline magmatism produced also skarn-type (e.g. *Bastnäs*) and

pegmatitic (*Ytterby*) REE and rare element deposits in the Bergslagen region (Goodenough et al. 2016). Younger Precambrian rocks of the ***Sveconorwegian Belt*** (collision of Fennoscandia and Laurentia into Rodinia, 930–920 MA) are less mineralised, an orthomagmatic Ti deposit at *Egersund* (SW Norway) can be mentioned only.

### Brief assessment

The province comprises almost exclusively Precambrian host rocks and ore deposits. All of these went through a complex deformation and metamorphic history, so original ore forming processes are mostly strongly overprinted, and sometimes hard to identify (Blundell et al. 2005). Heat flow is generally low in the area (Čermák et al. 1993). On the other hand, extension of all kind of deposits (even of stratiform and sedimentary origin) towards the depth appropriate for geothermal projects can be considered as a possibility.

## 5.2.2 Caledonides province

### Tectonics and mineralisations

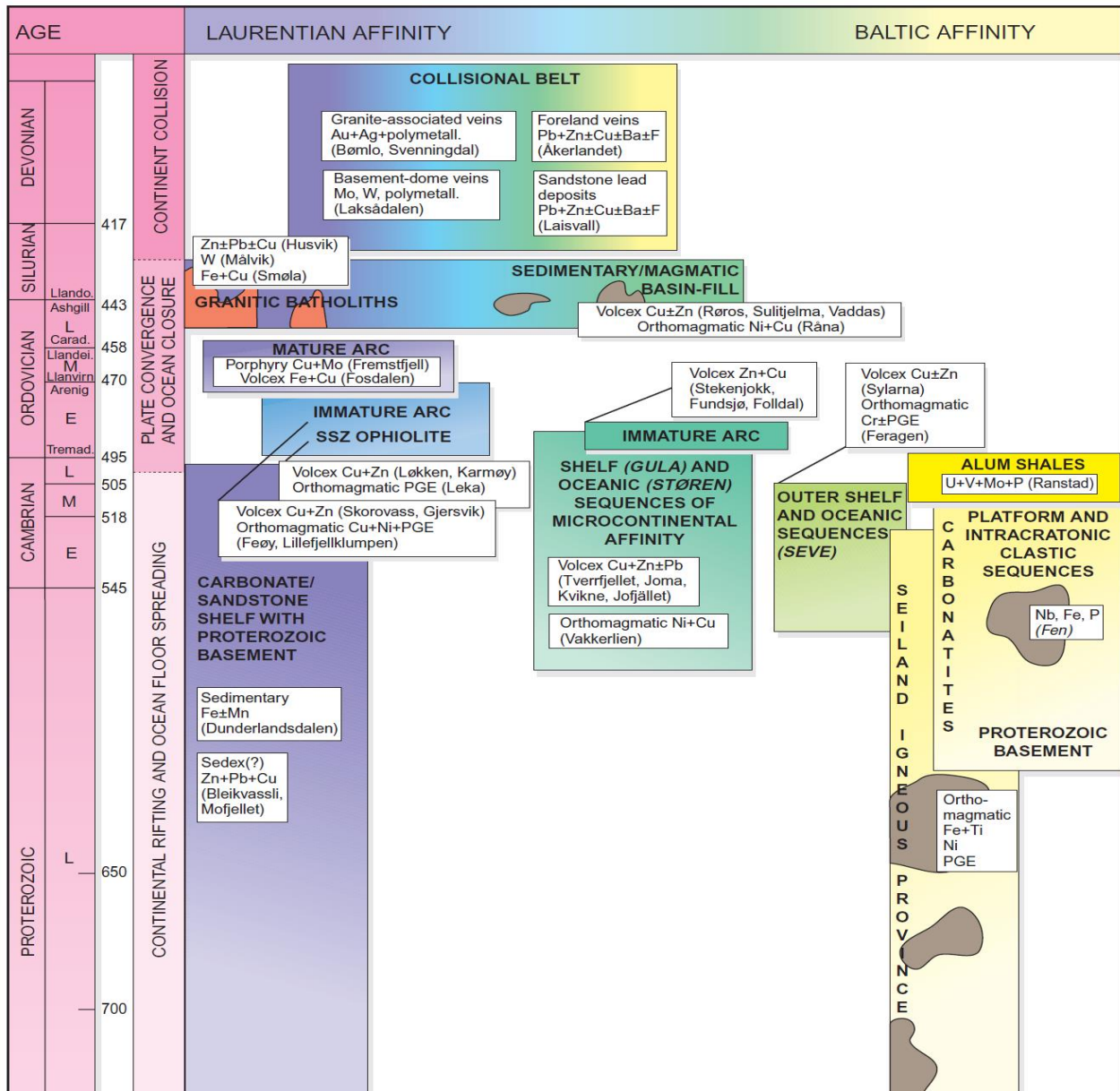
The ***Caledonides*** range through the Scandinavian Peninsula and the Northern part of the British Isles, forming a large metallogenic province (Plant et al. 1999) continued also on the American side of the Atlantic Ocean (Greenland and Eastern North America). Scandinavian deposits are summarised by Grenne et al. (1999) (Figure 5.2). Detailed information on the British commodities can be gained from the Mineral Reconnaissance Programme of the BGS (URL: [www.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html](http://www.bgs.ac.uk/mineralsuk/exploration/potential/mrp.html)).

The Caledonian orogeny started to develop in the Early Paleozoic with the closure of the Iapetus Ocean, incorporating the Eocambrian (700–600 MA) rifting phase and oceanic formations in the suture between Baltica and Laurentia. These pre-orogen formations include stratiform and stratabound base metal (Zn-Pb-Cu) sulphide deposits and magnetite-hematite Fe ores as the most important deposit types. Rift-related alkaline and carbonatite magmatism produced the *Fen Complex* with its Fe, Nb, REE and apatite deposits along with several similar bodies in the Caledonides, also with orthomagmatic Cr and Ni-Cu-PGE mineralisations. The passive margin of Baltica during the Cambrian was dominated by the sedimentation of the bituminous and pyrite bearing, 20-60 m thick *Alum Shale* with widely distributed U, Mo, Ni, V, As, Zn, Cd and Pb enrichment. This formation is a source of Cd, Cu, Ni and Zn contamination in the groundwater (Falk et al. 2006). It's known in outcrops and shallow setting, but in the Southern part of the distribution area (mostly in Denmark and Southern Sweden) hydrocarbon explorations drilled it below 1000 m depth also, and in the Danish-Norwegian Basin the depth of the Lower Palaeozoic succession exceeds 7 km (Lassen & Thybo 2012); the thickness can reach 100 m with tectonic repetitions (Grenne et al. 1999).

The subduction related volcanism started in the Early Ordovician, lasting to the Early Silurian. Both Zn- (*Stekeljokk-Levi*) and Cu- (*Løkken*) dominated VMS deposits are present in oceanic arc and marginal basin settings, while in active continent margin formations these deposits are scarce, and also scarce in the Grampian-Taconic orogen (British Isles). However, there are prospective regions (Hollis et al. 2014). Porphyry-type Cu-Mo-deposits are minor, but abundant in the province. Cu-Ni (*Aberdeenshire*) and PGE-bearing chromite (*Shetland*) is also present attached to mafic intrusions (Rice 2002). Granodioritic plutons and their country rocks may host some stockwork Cu-Mo, skarn and pegmatite Zn-Pb-Cu, Mo and W mineralisations.

The orogeny was divided into two phases (Plant et al. 1999). The Grampian phase means the collision of the Laurentian margin and oceanic arcs (475–460 MA); the Scandian phase covers the continental collision with Baltica (435–415 MA). In the South, also Gondwana-derived continental fragments are attached to the

Caledonides during the Silurian. These are named *Avalonia Terrains*, which are on the surface in England and in the Brabant-Midland Block but mostly covered by younger basin sediments in Northern Europe, and being partly involved also in the subsequent Variscan orogen. These can be regarded as parts of the Caledonides and the Variscides as well. The collision stage formations contain two important deposit types: sandstone- (e.g. *Laisvall*) and carbonate- (e.g. *North Pennine Orefield*) hosted stratabound base metal deposits (Pb, Zn, Ba, F, Cu) and vein-type Au, Ag, Pb, Cu, Zn, Fe, As, Sb, W, Mo and U enrichments formed at the depth of 8-10 km. Original stratiform ores can be deeply buried and partly remobilised.



**Figure 5.2** Significant deposit types and examples from the Scandinavian Caledonides (Grenne et al. 1999)

The province also comprises some significant post-Caledonian deposits, partly in the basin of the North Sea. Late Paleozoic rifting produced alkali intrusions in the *Kola Alkaline Province* (Goodenough et al. 2016) (apatite, Nb, REE) and the igneous complex of the *Oslo Graben* with Ag-bearing base metal veins, disseminated Cu-Mo mineralisation in felsic igneous rocks with attached Au, Ag, Pb, Cu, Zn mineralisation in quartz veins and iron skarn ore bodies (Bjørlykke et al. 1990). Contemporaneous volcanic products are attached to the Denmark and Skagerrak Grabens in the Central North Sea (McCann et al. 2006). In Ireland

stratabound Pb-Zn sulphide deposits (with *Navan* as the biggest example, Ashton 2005) were formed in the Lower Carboniferous sediments also with enrichments of Cd, Ag, As, Mn and Cu. MVT Pb-Zn, minor polymetallic vein type and stratabound deposits were also formed in England in the Late Paleozoic (Allen 1980). Several HC reservoirs of the Central North Sea area are known to contain also MVT Zn-Pb-Fe mineralisations in Mesozoic successions (Baines et al. 1991). The Northern Permian Basin succession (McCann et al. 2006) includes the Zechstein series (see Post-Variscan mineralisations). Ultramafic cumulates of the British Tertiary Volcanic Province (Northwest Scotland) contain minor PGE mineralisations (Pirrie et al. 2000).

### Brief assessment

The province provides several possibilities. The Alum Shale of Scandinavia can be a potential target of leaching. Experiments showed that sulphide-bound Cd and Mo can be easily mobilised by water; Cu, Ni and Zn had also fairly high mobilization rates (Lavergren et al. 2009), and HC prospecting may provide information and access in wells to the formation in the required depth. The low geothermal gradient of Scandinavia (Čermák et al. 1993) is a drawback like in the case of the Fennoscandian Shield, but deep-seated Danish and North Central European areas of the Avalonia Terrains can be prospective. A considerably higher geothermal potential is in Great Britain, where U-enriched granitoid bodies are the sources of heat (Busby 2010). Disseminated and quartz vein type precious and base metal sulphide mineralisations are attached to these bodies. Such bodies can be expected also in the buried continuation of Avalonia toward East in the continent. Irish or MVT type base metal ores may also occur in the basin regions.

### 5.2.3 Variscan province

#### Tectonic framework

The Variscan (or Hercynian) tectonic cycle started in the Devonian with the opening of the Rheic Ocean, and ended in the collision of Laurasia and Gondwana into the single continental mass of Pangaea during the Permian (Plant et al. 2005, Pohl 2011). Variscan ranges and basins are present in most of the Iberian Peninsula, in France, on Corsica and Sardinia, in Cornwall and in Central Europe North from the Alps and from the Carpathians. Lithostratigraphic megaunits comprising mostly metamorphic rocks and several deposits of Variscan origin are present also in terrains involved in the Alpine orogeny, but these will be treated as part of the Alpine Province.

In Central and Western Europe 3 East–West striking Variscan belts are distinguished from North to South; in Iberia the sequence of the equivalent zones is rotated to the opposite direction (Plant et al. 2005; Martínez Catalán et al. 2009). The **Rhenohercynian Basin** (Iberian equivalent: **South Portuguese Zone**) represents thick forearc basin (flysch-type) sediments extended also onto the East European Craton – most of this succession is covered by thick Permian and younger basin sediments, but explored by drillholes. Most important deposit types of this zone are rift-related VMS, intrusion-related and sediment-hosted (sedex or stratabound) ores, with some world-class deposits among these. The **Saxothuringian Belt** (Iberian equivalent: **Ossa-Morena Zone**) was the active margin of the continent with arc volcanism. The **Moldanubian Zone** (Iberian equivalent: **Central Iberian Zone**) comprises the high grade metamorphic lower crust of a microcontinent (Cadoimia) thrust onto the Laurasia-derived Armorican terrains. In the latter zones various magmatic-hydrothermal or hydrothermal deposits are common, but deposit sizes are smaller. Most important deposits are linked to granitic intrusions. In Southern France and in Iberia further belts are distinguished.

Large areas of the Variscan terrains are covered by Meso-Cenozoic basin sediments in a thickness of several kilometres: basins of Iberia, *Aquitaine Basin*, *Paris Basin* and the *Central European Basin System*. The

basement of these may consist of the continuations of the zones above, including the subduction front between Rhenohercynian and Saxothuringian Zones represented by the Lizard Ophiolite Complex in Cornwall on the surface, but composition and mineralisation of this hidden basement is unknown.

**Pre-Variscan and foreland mineralisations**

The Variscan province includes the inherited formations of the Neoproterozoic *Cadomian Orogenic Belt* in Armorica (NW France), Bohemia and Iberia. In the Armorican Massif volcanosedimentary and hydrothermal-sedimentary polymetallic sulphide deposits and cassiterite-wolframite-bearing granitic intrusions were inherited from this period (Chauris & Marcoux 1994). In Bohemia (Teplá-Barrandian Unit) Cyprus-type hydrothermal polymetallic ores, in the Jílové Belt (or Central Bohemian Metallogenic Belt) orogenic and intrusion-related gold are present, but also stratiform Cu-Zn-Au sulphide mineralisations are deposited on original top regions of basic, intermedier and acidic metavolcanics. BIF-type Fe-V-U and pyrite-bearing black shale locally enriched in Ni, Zn, Mo and Cu (but not Pb) sulphides are hosted by metasediment successions (Morávek & Pouba 1987; Mrázek & Pouba 2013). In Iberia VMS base metals (Cu, Pb, Zn), barite and Zn-Pb sedex deposits and some minor porphyry copper mineralisation occur in the Ossa-Morena Zone (Tornos et al. 2004). Deep-seated, hidden Cadomian mineralisations may be the source rocks of several later Variscan deposits, e.g. Sn and Cu supply of the Neves-Corvo deposit probably has come from a Cadomian granite body (Ribeiro et al. 2014).

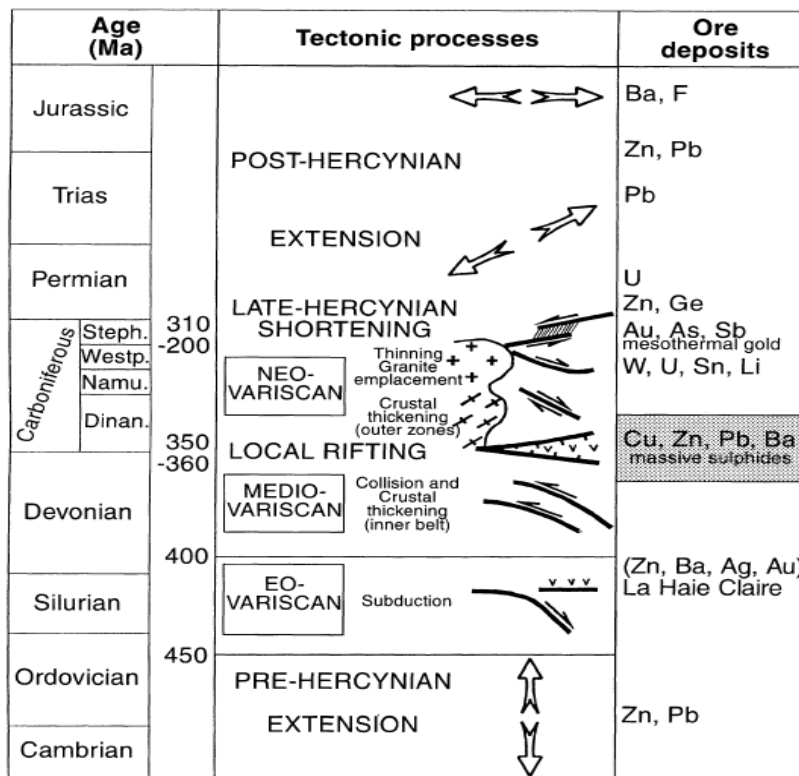


Figure 5.3 Metallogenic events related to the Variscan orogeny in France (Lescuyer et al. 1998)

*Pre-Variscan extensional tectonics* produced several mineralisations in the province (Figure 5.3). In the Rhenohercynian Basin sedex-type Zn-Pb deposits (*Meggen, Rammelsberg*) and, adjacent to mafic intrusions, *Lahn-Dill* type Fe, Ni-Cu and Hg deposits were formed (Mucchez et al. 2005, Walther 1982); small occurrences are located also in the other Variscan belts (Mrázek & Pouba 2013). Sedex and MVT Zn-Pb deposits together with stratabound Sb-Hg-W-As ores are also present in Sardinia (Mederer & Chelle-Michou 2011) and in Iberia. The Llandoveryian black shales of Catalonia contain sedex apatite and polymetallic (also Au, Ag and

PGE) deposits (Canet et al. 2004). At Almadén (Central Iberian Zone) a huge stratabound cinnabar (Hg) mineralisation hosted by quartzite is connected with mafic volcanism (Palero-Fernández et al. 2015). In Armorica massive sulphide and black shale hosted Pb-Zn-Cu deposits were mined (Besson 1982) (Figure 5.4). There are further small examples of Cu mineralisation: the Lizard Ophiolite Complex (Cornwall) hosts tectonically reworked Cu ore (Allen 1980) and a diorite intrusion hosts a porphyry Cu-Mo deposit at *Herzogenhugel*, Belgium (Suthpin et al. 2013).

**Organic-rich sediments** (black shales and coal) explored for HC, mainly in the succession of the Rhenohercynian Basin, are of interest also as metal sources. Carboniferous coal seams of the region are often associated with pelosiderite deposits (Fe ores) enriched locally in Mn and base metals; enrichments were found in the coal itself (Laznicka 1985). In the Lower Carboniferous underlying strata of the coal bearing series two horizons can be mentioned, called Lower and Upper Alum Shale in Germany, widely distributed in the successions developed also on Avalonian basement to England and to the North Sea. These reach more than 100 m of thickness, but their typical pyrite content is lower than 3% (Ulfmann et al. 1912). Silurian and Lower Devonian 'alum shale horizons' in graptolite shales of similar facies in the Saxothuringian Zone hosted V, U and base metal (mainly Mo, Zn) sulphide enrichments, which were locally exploited as ores in Thuringia (Dill 1986).

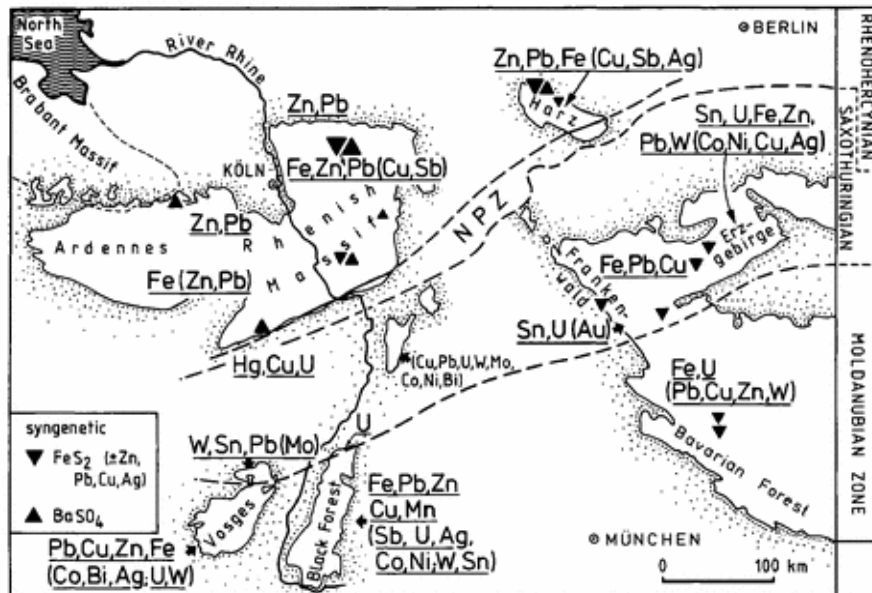
### Variscan mineralisations

On the Iberian Peninsula and in France Late Devonian–Early Carboniferous local **rift-related bimodal volcanism** produced several VMS deposits associated with felsic volcanics: *Chessy* and *Chizeuil* in the Massif Central; *Bodennec* and *La Porte-aux-Moines* in the Armorican Massif; *Rio Tinto*, *Neves-Corvo*, *Tharsis* and several others in the Iberian Pyrite Belt (IPB) far exceeding the French deposits in size (Lescuyer et al. 1998, Leistel et al. 1998). The main ore elements are Cu, Pb, Zn, Ag and Au, associated with Sn, Bi, Co in the IPB and with Mo, Ni in the Massif Central. The 240–50 km long and 25–70 km wide IPB is located in the South Portuguese Zone, and the ores are hosted by a volcano-sedimentary sequence either in black shale or lying on the top of rhyolitic volcanics. Estimated ore resources of the known deposits range to 1700 Mt altogether. The IPB developed in a transtensional geodynamic setting related to the Northeast-vergent subduction under the Ossa-Morena Zone; host rock bodies of the belt dip to North generally and may continue to the depth.

The Ossa-Morena Zone, overriding plate of the subduction zone, comprises a large number and variety of ore deposits, but neither of these compares with the importance of the IPB. **Synmetamorphic and granite-related** base metal-bearing veins, small volcanic-hosted polymetallic massive sulphide deposits, iron oxide replacements and skarns, magnetite and Cu-Ni magmatic ore bodies, Sn-W veins and replacements and orogenic Au mineralisation are present here. Relatively low temperature orthomagmatic Fe-Ti-V and Ni-Cu mineralisations are attached to felsic and mafic intrusions, respectively; epithermal Cu-Ag-Au is also present. An extended ultramafic body in the middle crust can have played a significant role as a source of the hydrothermal fluids (Tornos et al. 2004, 2005). In Galicia (NW Spain) Li-bearing pegmatites and Sn-W veins are attached to synorogenic granite, while disseminated and massive Cu-Fe-base metal sulphides to metamorphosed ophiolitic complexes (Ypma 1966, Badham & Williams 1981) in an area of enhanced heat flow (Chamorro et al. 2014). Similar mineralisations occur also in Sardinia and Corsica attached to granite intrusions (Mederer & Chelle-Michou 2011).

In the Saxothuringian and Moldanubian zones the mineralisation is more significant, especially in the Erzgebirge (Krusné Hory). The veins and stockwerks in the metamorphic country rocks of granite bodies contain Ag and U ore at *Jáchymov* (Erzgebirge) and *Příbram* (Central Bohemian Mobile Zone), associated

with polymetallic enrichment; at *Cínovec* and *Altenberg* greisen-type Sn-Li-W deposits were mined. Another historical Ag-Pb-Zn-Cu deposit, *Andreasberg* is located in the Harz Mts (De Vos et al. 2005). At Marsberg (Rheinisches Schiefergebirge) a sulphide stockwork deposit was mined (Walther, 1980). In Lower Silesia porphyry Cu-Mo deposits were explored with associated skarn mineralisations in and around granodiorite, monzonite and rhyodacite bodies (Haranczyk 1980) (Figure 5.4).



**Figure 5.4** Variscan metallogeny of the Central European Variscides in Germany (Werner & Walther 2013)

Late Carboniferous–Early Permian **granitic intrusions** are associated with cassiterite-magnetite-beryl (Sn, W, U, Fe, Be) greisen, vein and skarn deposits containing also Cu-As or Au-Bi-Te minerals, and polymetallic lodes in the Massif Central, in Brittany (France), in Northern Portugal, in Northwest Spain (Galicia, Asturia) and in Cornwall, Cornubian Ore Field (Besson 1982, Scrivener 2006). In France, Sn, Cu, W and Mo is conjugated mostly with subalkaline and aluminopotassic granitoids, Sn-W-Li-Be-Nb-Ta mineralisations occur in sodic subalkaline rocks (mostly leucogranites), U in potassic leucogranites, while calc-alkaline rocks are barren (Stussi 1989). In Portugal the *Panasqueira* Sn-W bearing quartz veins are world-class (De Vos et al. 2005). Late-stage alkaline intrusions produced REE-enriched pegmatites in the Bohemian Massiv (Goodenough et al. 2016). In the Craców-Silesian orogenic belt porphyry Cu-Mo deposits are identified (Suthpin et al. 2013).

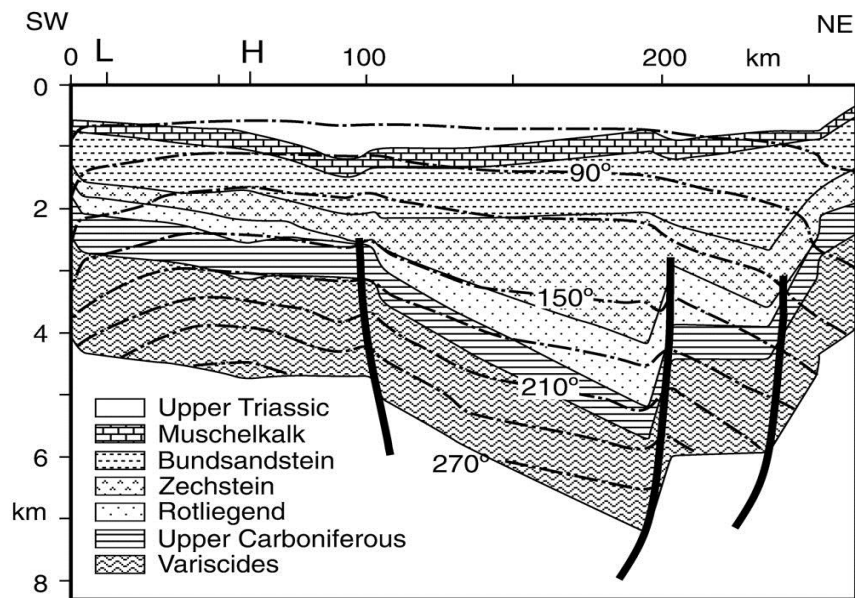
**Hydrothermal mineralisations** without known magmatic source are present in several regions of the province: e.g. Pb-Zn- and Cu-dominated lodes, Hg replacements and uranium-bearing veins in the Ossa-Morena Zone (Tornos et al. 2004), dolomite hosted Zn-Pb in the Picos de Europa province (Northern Spain, Gómez-Fernández et al. 2000), Sb-Hg in the Cantabrian Zone (Martín-Izard et al. 2009), Pb, Zn, Sb in Armorica, “orogenic” Au, Cu, As, W, Bi in the Massif Central (Besson 1982); Pb-Zn vein systems together with sediment-hosted, partly non-sulphide ores (*La Calamine*) in Belgium (Dejonghe 1998) and in Germany. The development of polymetallic vein mineralisations was continued also in Post-Variscan time (Walther 1980).

### Post-Variscan mineralisations

**Post-orogenic subsidence** of basins in North Central Europe and England (Central European Basin System) and a rapid transgression (~258MA, ‘Zechstein Sea’) has led to the formation of a thin (0.3–4 m), but widely distributed bituminous marl horizon enriched mainly in base metals, called *Kupferschiefer* (Vaughan et al. 1989, Zientek et al. 2015). The main ore elements are Cu, Pb and Zn in small sized (20–200 µm) sulphide minerals, but V, Mo, U, Ag, As, Sb, Hg, Bi, Se, Cd, Tl, Au, Re and PGE are also enriched and were extracted in



some occurrences. The horizon lies on barren sandstone ('Rote Fäule') and is covered by carbonate (Figure 5.5). The initial stratiform mineralisation of low concentration was enhanced to some percents of base metals by late diagenetic processes dated to the Early Triassic (Mucchez et al. 2005). The burial depth can reach several kilometres (Bechtel et al. 2000, Oszczepalski & Speczik 2011). Prospective and mining areas were summarised by Zientek et al. (2015).



**Figure 5.5** Cross section of the Polish basin, reconstructed for the Late Triassic with isotherms of reconstructed temperatures on the basis of thermal modelling. H: centre of Permian-Jurassic heat flow anomaly, L: Lubin (Blundell et al. 2003)

Beyond Kupferschiefer, in Silesia the Polish Basin contains MVT Pb-Zn-Ag mineralisations hosted mainly by the Middle Triassic 'Muschelkalk' formation, with 30 Mt estimated reserves (De Vos et al. 2005). Several minor stratabound or vein-type U, base metal, Fe-Mn (e.g. 'minette' ore) and placer-type Au-Sn occur in the basins evolved on Rhenohercynian, Saxothuringian or Moldanubian basement in Germany and in the Czech Republic (Dill 1994). In Southern France Triassic or later Pb-Zn-Ag deposits are hosted in quartzite (Besson 1982).

Triassic evaporitic successions contain stratabound MVT or organic-rich shale hosted Pb-Zn deposits related to salt diapirs in the Vocontian and Cantabrian Basins (Rouvier et al. 1985). Traces of significant brine migration and vein mineralisation of the same geochemistry as the Pb-Zn(-F-Ba) deposits of the Western Massif Central and the Pyrenees was found at the granite-sediment contacts in the Aquitaine Basin (Boiron et al. 2002). Stratabound U mineralisation occurs in graben filling sediment of the Vosges. Significant Toarcian oolitic iron ore deposits are in Lorraine (Besson 1982).

### Brief assessment

The province is rich in potential targets. Cadomian remnants, Variscan active margins with intrusive bodies and sutures with ophiolites may be fertile, but best targets are the widely distributed and voluminous massive ore bodies and sulphide-enriched sedimentary horizons hosted by thick foreland basin successions. Most important of these are the VMS deposits of the Iberian Pyrite Belt and the Kupferschiefer horizon known from outcropping occurrences, but continued toward the depth. Iron ores and black shales in the underlying succession of the Carboniferous coal bearing series can also contribute to the metal producing potential. The evaporitic country rocks (presence of salt rocks and saline formation water) of the Permian Zechstein polymetallic and the Southwest European Mesozoic Pb-Zn deposits may enhance the leaching

possibilities. In fact, high salinity and high Fe, Zn, Pb, Ba, Sr content likely to precipitate (as pyrite, galena, barite, celestine) was measured in geothermal waters in the North German Basin (Regenspurg et al. 2010; Vetter et al. 2010).

A considerable part of these formations lies under thick Meso-Cenozoic successions of basins with fairly high heat flow rates, like in the Paris Basin (Lucazeau & Vasseur 1989) or in the North German Basin, where the temperature exceeds 100°C below cca. 2500 m (Agemar et al. 2014). Operating low-temperature geothermal production plants of France are concentrated in the Paris and Aquitaine Basins (Laplaige et al. 2005). Heat flow can be large especially at Cenozoic rift zones or sites of magmatism (Auvergne and Massif Central, France; Rhine Graben and Eifel region, Germany; Eger Graben, Bohemia; Plant et al. 2005) (Figure 5.6).

Vein and stockwerk-type polymetallic sulphide mineralisations hosted by contact aureoles of granite bodies can be of interest especially if the enhanced U-content of the intrusive body contributes to an elevated heat production, like in Cornwall (Busby 2010), Brittany, the Massif Central (Lucazeau & Vasseur 1989) and in the Erzgebirge (Förster & Förster 2000). Such bodies can be expected also in the basement of the Aquitaine and the Paris Basins. A deep geothermal pilot plant at Soultz-sous-Forêts (Alsace) explores Carboniferous monzogranite of 200°C temperature in the 4250–5000 m depth interval of the Rhine Graben (Dezayes et al. 2005, Laplaige et al. 2005).

Enhanced heat flow makes prospective the massive sulphide deposits in Galicia (Chamorro et al. 2014), where great abundance of hot springs and seismic activity is attached to deep-reaching fault systems (Sanchez-Guzmán & Garcia-de-la-Noceda 2010).

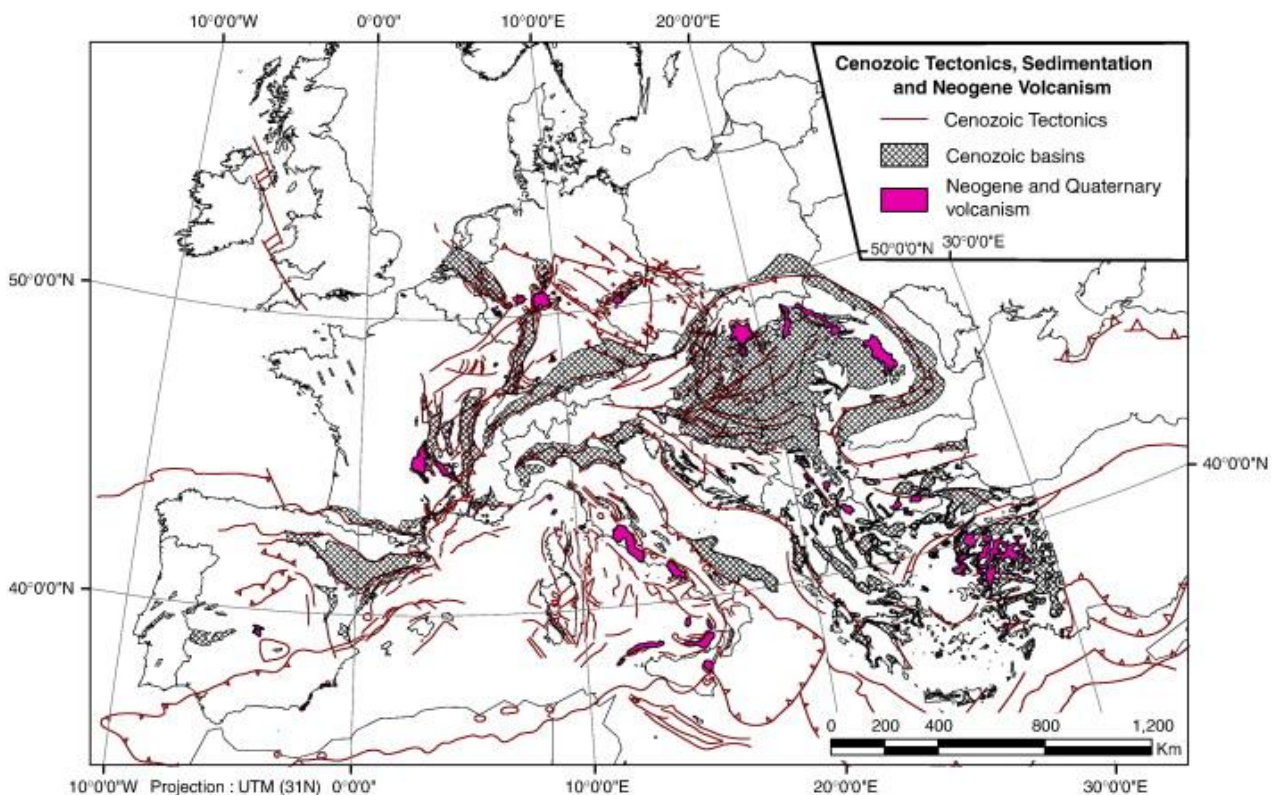


Figure 5.6 Cenozoic basins, rifts and volcanism of Europe (Cloething et al. 2010)

## 5.2.4 *Alpine province*

### General tectonic framework

The Alpine Orogenic Belt ranges from the Atlas to the Caucasus across Europe, continued further in Asia. The orogeny developed from the closure of the Tethys Ocean, so the whole system is often referred to as Tethyan province, but as we deal with the European portion only, Alpine is the more appropriate name. The belt comprises the following ranges from west to East: Betic Cordillera, Pyrenees, Alps, Apennines, Carpathians, Dinarides, Balkan and Hellenides (Richards 2015, Pohl 2011, Plant et al. 2005).

Rifting and fragmentation of Pangaea initiated the Alpine tectonic cycle in the Late Permian. Triassic successions were deposited in continental and shallow marine environments. The opening of the Tethys Ocean, separating Laurasia from Gondwana again, and the also started opening of the Atlantic Ocean was marked by a magmatic pulse which can be traced across the continent, and a major transgression invaded the present-day sedimentary basins. The tectonic regime turned into contractional in the Early Cretaceous in the Tethys Basin, while it continued to be extensional at the Atlantic margin with rifting-related magmatism in the Pyrenees region up to the Late Cretaceous.

On other parts Late Cretaceous was the time of culmination of metamorphism and nappe emplacement in the collisional zone, and of subduction-related arc-type volcanism in the Banatite Magmatic and Metallogenic Belt in the Southeast and further in Asia. Cenozoic era was the time of uplift and erosion down to the metamorphic core of several mountains and the sedimentary earthing up of several intracontinental basins coupled with volcanism. All of these tectonic processes of convergence between Europe and Africa are still active in the region; enhanced heat flow is attached to basins with thinned lithosphere, active magmatism or volcanism ceased within a few million years only mainly in South and Southeast Europe (Figure 5.6).

### Mineralisations of the Betic Cordillera

The Betic Cordillera formed in Late Cretaceous-Paleogene subduction and then in a postcollisional extension tectonic regime up to the Miocene (Weijermars 1991). The metamorphic core comprises of the Paleozoic rocks of the Variscan belts and its Permian-Triassic cover, the external (Prebetic or Subbetic units) of non-metamorphic nappes of Mesozoic-Cenozoic rocks. The Neogene Almería-Cartagena volcanic belt evolved from calc-alkaline to alkaline rocks. Three groups of polymetallic ores are present (Arribas & Tosdal 1994):

- carbonate-hosted stratabound F-Pb-Zn-Ba;
- hydrothermal vein- and manto-type deposits of Pb, Zn, Fe and Ag with Ba, Cu, Sn and Sb;
- epithermal veins of Pb-Zn-Ag-Cu-Au and Au-Cu-Te-Sn.

PGM-enriched chromitite deposit is attached to uplifted mantle rocks, the Ojen lherzolite block (Torres-Ruiz et al. 1996).

Temperature exceeding 150°C can be reached in this region in Triassic and Jurassic carbonates in the 2500–3500 m depth range (Sanchez-Guzmán & Garcia-de-la-Noceda 2010).

### Mineralisations of the Pyrenees

The Pyrenees preserved the Late Carboniferous Variscan structures with regional metamorphism and granitoid intrusions. Permian and Triassic magmatism was associated with rifting and opening of the Atlantic Ocean. The collision phase, after cessation of Mesozoic rifting, started in the Late Cretaceous and lasted to the Late Oligocene, but it lacks a prograde metamorphic overprint. Along the North Pyrenean Fault Zone alkali magmatism with enhanced REE contents evolved on extremely thinned lithosphere, in the South

tectonic inversion of Mesozoic basins was characteristic. Eastern Pyrenees were affected by extension processes in the Neogene (Banda & Wickham 1986, Vergés et al. 2002).

The ore deposits of the Pyrenees are scarce and of minor importance in general. Most widely distributed deposits are Pb-Zn ores in the area associated with fluorite. In the Central Pyrenees three different Paleozoic sediment-hosted Zn-Pb-F-Ba deposit-types occur: sedex deposits hosted by clastic sediments; crust-type mineralisations in carbonate sequences; Post-Variscan vein mineralisations (Subías et al. 1999).

The shelf-margin facies Urgonian limestone and dolomite of the Basque-Cantabrian Basin in the North Pyrenean Belt hosts several Pb-Zn deposits of sedex, stratabound or vein types. The largest is the Reocín stratabound Pb-Zn deposit with cca. 60 Mt ores containing 8.7% Zn and 1.0% Pb (Velasco et al. 2003; Águeda Villar & Salvador González 2009).

The Pyrenees are rich in hot springs and active geothermal systems. A temperature of 150 to 170°C was found in Eocene and Palaeocene carbonate reservoirs of the Jaca/Sabiñánigo area in the 2800–3500 m depth range (Sanchez-Guzmán & Garcia-de-la-Noceda 2010).

### **Mineralisations of the Apennines**

The Apennines started to evolve in the North from the accretionary prism at the Apulian microplate during the Cretaceous. The main orogenic period was the Oligocene collision of Sardinia and Corsica with Apulia, up to the Tortonian. The Neogene extensional regime brought the opening of the Tyrrhenian Sea basin. In the North it is a continental rift, but in the South a back-arc spreading is going on behind the subduction zone of the Ionian microplate under the Calabrian arc (Lattanzi 1999).

The significant ore deposits of the Apennines are concentrated to the Northern region. Oligocene-Miocene calc-alkaline and also Quaternary volcanism in Tuscany, on Elba, on Corsica and on Sardinia produced several epithermal deposits of Sb, Hg, Au and Ag. Au occurs in quartz vein- and carbonate-hosted (Carlin-type) deposits. Some geochemical characteristics indicate remobilisation of mineralisations from the Precenozoic basement (Lattanzi 1999). In the '*Colline Metallifere*' district and on Corsica base metal deposits are important as well. Skarns are also attached to the volcanic-hosted ore bodies. The Mt. Amiata mining district comprises of world-class Hg deposits, mostly replacement ores in carbonate under impermeable overlying strata, related to recent geothermal systems. Geothermal power plants of the region have significant Hg emission (Rimondi et al. 2015).

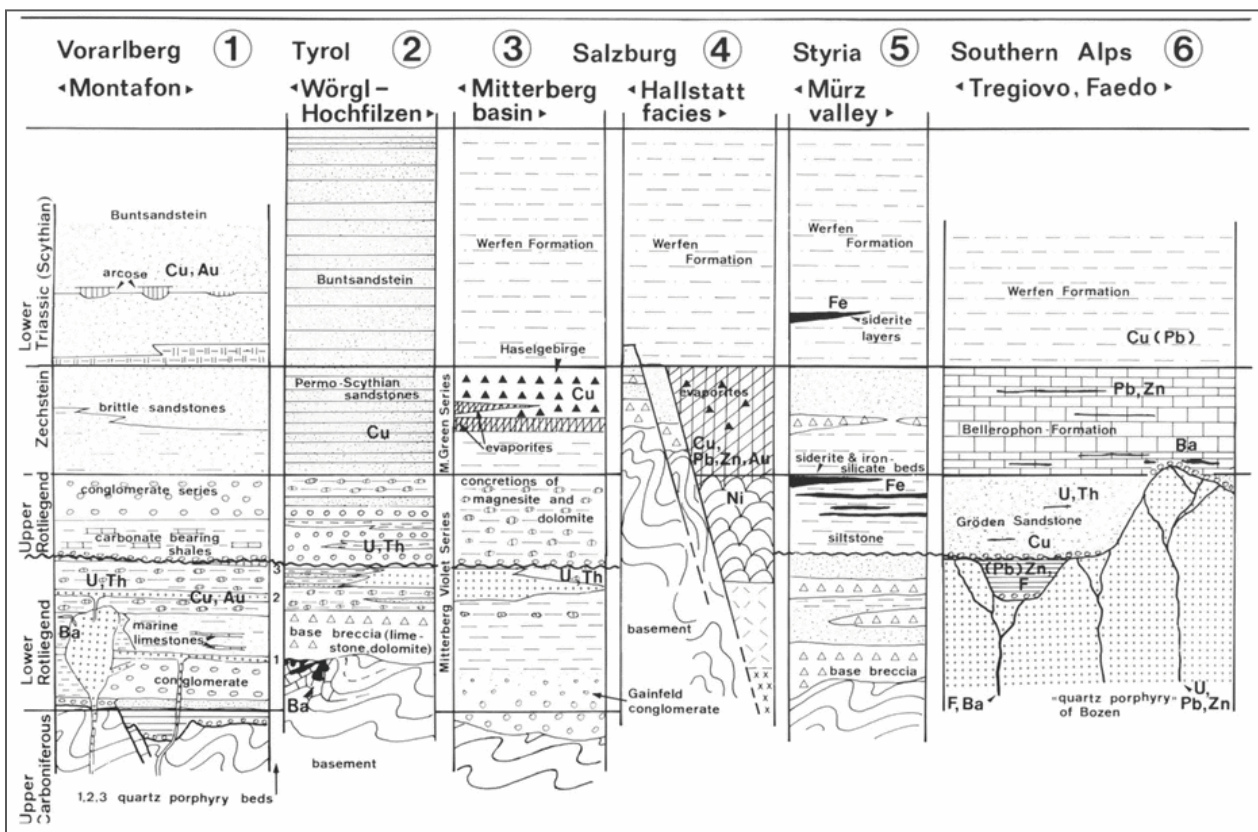
Beyond these regions, the Calabria-Peloritani arc in Sicily contains minor Prealpine polymetallic and precious metal mineralisations with a metamorphic overprint (Saccá et al. 2007). VMS and attached stockwork and vein type Fe-Cu-Ni-Zn-Pb-sulphide with Au enrichment are common, PGE-bearing chromitites and stratiform Mn (braunite) deposits also occur in Mesozoic ophiolite complexes of the Northern Apennines (Bonatti et al. 1976, Zaccarini & Garuti 2008).

The Apennines are characterised by Quaternary volcanism from South Tuscany (Larderello geothermal field) to Sicily (Etna). There are active hydrothermal systems with several hot springs, where the water bears naturally elevated metal contents (e.g. Duchi et al. 1986, Sedwick & Stüben 1996); the Etna volcano also emits large amounts of various metals in gas phase as aerosols (Calabrese et al. 2014). Investigation of the alkali volcanics of the Vesuvius indicated the possibility, but no direct evidence of any precious and base metal sulphide mineralisation (Paone et al. 2001). There are indications of REE enrichments in alkali volcanics all over the region (Goodenough et al. 2016).

### Mineralisations of the Alps

The range of the Alps was the product of the collision of Europa and the Apulian microplate, started in the Late Cretaceous after the closure of the several minor oceanic basins existing at the western part of the Neotethys. Oceanic crust was subducted beneath the Apulian plate. The suture is marked by the Periadriatic Seam. Complex nappe systems were formed including exhumated metamorphic rocks with inherited Pre-Alpine mineralisations, Permian–Mesozoic basin sediments and related magmatic rocks, and synorogenic foreland or intramontane molasses and flysch basins. The convergence is still going on recently. Detailed structural division is given by Schmid et al. (2004). Data of deposits of the Eastern Alps are summarised with a metallogenic map by the Geological Survey of Austria (Weber ed. 1997).

There are several Prealpine deposits in the region, sometimes with Alpine metamorphic overprint. Polymetallic and W-Sb-Hg deposits were inherited from Paleozoic magmatic-hydrothermal processes (Höll 1977). The scheelite (W) deposit (also enriched in Sn, U and F) at *Felbertal (Mittersill)* in the tectonic window of the High Tauern hosted in gneiss is a world-class deposit (Weber ed. 1997). Fe-Ni-Cu sulphides with PGE enrichment occur in the basic rocks of the 'suture zone' (Garuti & Rinaldi 1986). The 'Grauwackenzone' is known for several polymetallic (Cu, Fe, Ni, Co, Hg) sulphide deposits (Weber ed. 1997). Sedex Pb-Zn-Ag deposits are characteristic in the Graz Paleozoic Complex (Weber 1990). Significant stratiform and stratabound ore deposits are hosted by the Permian–Jurassic sedimentary successions (Figure 5.7).



**Figure 5.7** Correlation chart of the Permian–Lower Triassic mineralisations of the Eastern Alps (Haditsch & Mostler 1982)

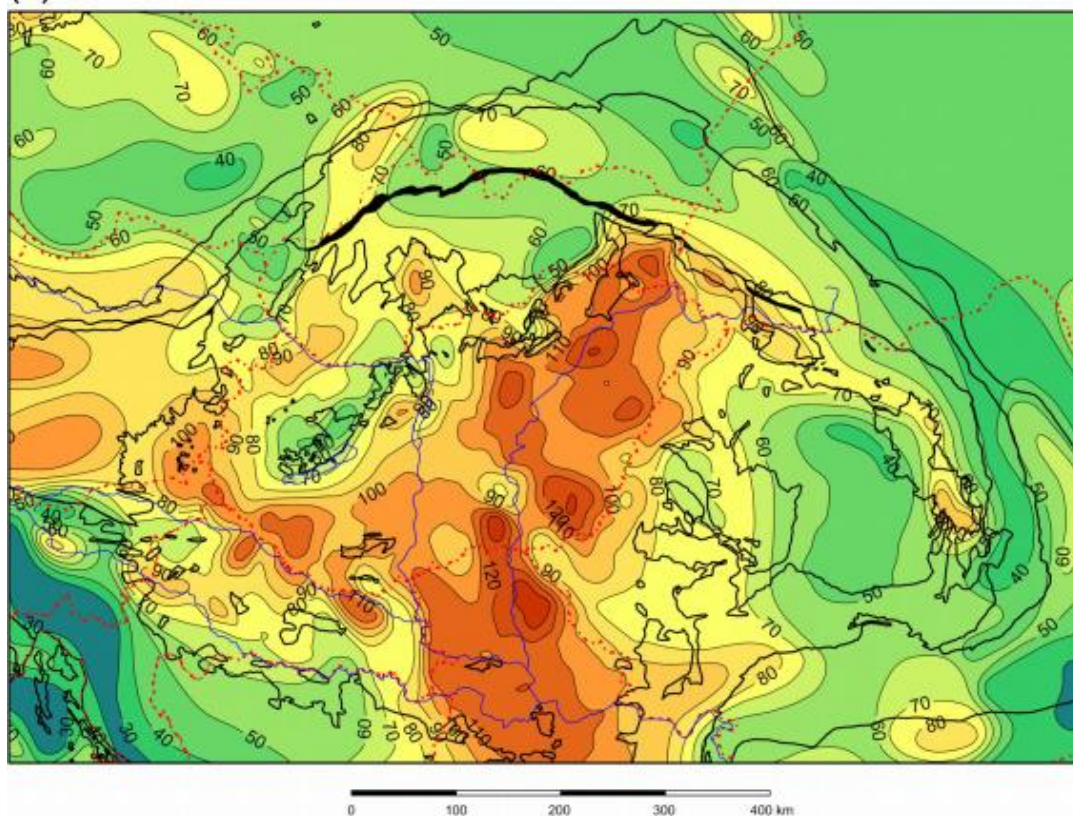
Carbonate-bound, MVT Pb-Zn deposits are widely distributed; these occur also in the Western part, but most significant are the deposits of the Southern and Eastern Alps (e.g. *Salafossa, Raibl, Bleiberg, Mežica*) (Cerny 1989). Permian halite of Tirol also contains galena and other sulphides. Toarcian stratiform rodochrosite (Mn) deposits or Mn- and organic matter-enriched black shales are hosted by marl in the 'Kalkalpen' (Weber

ed. 1997). Triassic alkaline magmatism in the Southern Alps (Trento, Italy) produced W-Mo-Sn-Bi and polymetallic sulphide deposits related to granite intrusions (Frizzo et al. 2010). Synorogenic mineralisations in the Eastern Alps formed Ag-Cu bearing quartz- and barite-veins and replacement type Fe deposits (e.g. Erzberg siderite) typically. Au- and Sb-enriched quartz veins, mesothermal gold lodes (e.g. the 'Tauerngold', or the Monte Rosa Gold District) are considered as postorogenic (Pohl & Belocky 1999).

Elevated heat flux areas are in the Northern foreland of the Alps, the Molasse Basin (Agemar et al. 2014) and the Jura Mountains affected by the Cenozoic rifting (Sonney & Vuataz 2008). Brown coal bearing and organic matter-enriched formations of the basin may host widely distributed accumulations of metals. Geothermal fluids of the Molasse Basin are slightly acidic and saline (Vetter et al. 2010), with high sulphide content in the central part (Mayrhofer et al. 2014).

### Mineralisations of the Carpathians

The arch structure of the Carpathian Range with the Pannonian Basin in its centre evolved by the escape and rotation of two microplates (referred to as Alcapa and Tisia blocks) during their movement towards the East European Craton. The two microplates contact at the SW-NE striking Mid-Hungarian Mobile Belt (Csontos & Nagymarosy 1998), a continuation of the Periadriatic Seam of the Alps, mostly covered by Neogene basin sediments. The Alcapa-based, from SW-NE to W-E striking ranges are named **Western Carpathians**, the Tisia-based ranges in Ukraine and Romania are the **Eastern** and **Southern Carpathians**. In the outer part of the arch an uplifted collisional zone was formed with nappesystems, flysch and molasse basins, while the inner part is a mosaic of variably uplifted and subsided terranes during the Cenozoic. Inside the arch, the **Pannonian Basin** was formed mostly in the Neogene extensional regime, and has a high geothermal potential (Horváth et al. 2015) (Figure 5.8).



**Figure 5.8** Heat flow map of the Pannonian basin and surrounding regions (heat flow values in  $\text{mW/m}^2$ ), corrected for (where appropriate) the cooling effect of fast sedimentation (Horváth et al. 2015)

The Pre-Cenozoic, partly metamorphic sequences host several inherited, reworked, but also newly formed ore deposits. MVT Pb-Zn, minor stratiform Fe and basic volcanism-related VMS deposits occur in the Rodna Mts and the Rebra Paleozoic, Eastern Carpathians. Kuroko-type VMS deposit occurs at *Tulghes*. Lahn-Dill type Fe deposits and rhyolitic volcanism-related base metal sulphide veins are typical in the Poiana Rusca Mts. in the South (Kräutner 1996). Stratabound (metasomatic), often black shale-hosted and vein type siderite, barite and base metal sulphide mineralisations are most abundant in the Paleozoic of the Slovakian Ore Mountains, but also present in metasomatised Triassic carbonates in NE Hungary (*Rudabánya*).

The granite bodies of this region are also associated with Sn-W-Mo and U-REE-Au lodes. U-Mo-Cu and magnetite deposits of the Slovakian Ore Mts, Sb-Au and W-Au deposits in the Low Tatra and the Small Carpathian Mts. are further important mineralisations in the Western Carpathian region (Grecula et al. 1996). Stratiform Mn mineralisations occur in several localities hosted by Toarcian and by Oligocene black shales (Rojkovič et al. 2008), the *Úrkút* Mn deposit (Hungary) is also enriched in REE (Grasselly & Pantó 1988).

Two major calc-alkaline volcanic series evolved in the region (Sillitoe 1980, Harangi 2001, Richards 2015). The Late Cretaceous–Paleocene suite ‘banatites’ are characteristic for the trenches of the Southern Carpathians, continued also in the Balkan Range, most probably formed by subduction of the Vardar Ocean basement (a branch of the Neotethys). The Oligocene–Miocene suite forms the ***Inner Carpathian Volcanic Chain*** South of the main ranges of the Western Carpathians (Slovakia and Hungary), the volcanic mountains of the Eastern Carpathians and the ***Apuseni Mts.*** (Romania) in a post-collisional extension regime. All of these are dominantly andesitic, but dacites and, mainly from the Miocene, rhyolites are also voluminous. Beyond these, some alkaline, mostly basic volcanic suites are also present in the region, but with no ore deposits of importance.

The multiple calc-alkaline volcanic phases of the Carpathians are associated with a series of porphyry copper and conjugated skarn, epithermal (HS and LS) Au and base metal (Cu, Pb, Zn) sulphide deposits, making this ore subprovince one of the world’s major base metal reserves (Sillitoe 1980). Major ore complexes are bound to large volcanic caldera structures with several subvolcanic intrusive bodies and extensive rock alterations. Most large deposits of the earliest, Meso-Cenozoic ‘banatite’ region are in the Balkan area (see mineralisations of the Balkans and the Hellenides); the *Moldova Noua* porphyry Cu-Mo deposit in the Banat Mts and the skarn deposits of the Apuseni Mts. are here of importance (Quadt et al. 2005).

Late Paleogene volcanism in the vicinity of the Mid-Hungarian Mobile Belt, active as dextral strike-slip zone at this time, produced several minor volcanic bodies and attached polymetallic sulphide mineralisations, of which the *Recsk* porphyry Cu-Au with attached skarn and epithermal ores is the most significant (Baksa et al. 1980). In the Miocene Inner Carpathian Volcanic Chain the deposits of the *Štiavnické Mts* (a traditional precious metal mining district) and the vicinity of *Baia Mare* can be mentioned as most prominent, although all volcanic edifices host at least vein type epithermal deposits (Neubauer et al. 2005).

It is important to notice that several volcanic structures continue in buried position under thick Late Miocene–Quaternary sediments of the Great Hungarian Plain in the Northeast, downthrown by fault zones of the Mid-Hungarian Mobile Belt (Harangi 2001). A separate, but even more important area of this volcanic period is the ore district ‘*golden quadrangle*’ in the Metaliferi (Ore) Mts (part of the Apuseni Mts.) with deposits like *Roşia Montana* epithermal Au-Ag, *Roşia Poieni* and *Bucium-Tarnita* porphyry Cu also containing Au and Ag (Neubauer et al. 2005). Unexploited Au reserves still are estimated to exceed 1000 t (Popescu & Neacşu 2012).

## Mineralisations of the Dinarides

The Dinarides form a NW-SE striking range between the Adriatic Sea and the Pannonian Basin, connecting the Alps with the Hellenides. The successions from the Permian to the Jurassic correspond or resemble to the Southern Alps, but presence of Triassic rifting-related volcanics is characteristic. Shortening started from the Late Jurassic; on the Northern edge subduction of the Vardar Ocean lasted to the Eocene, and an accretionary wedge was formed. Four major tectonostratigraphic units can be defined: Adriatic-Dinaridic carbonate platform; carbonate and clastic formations of the passive continental margin (Bosnian flysch) (*External Dinarides*); Dinaridic ophiolites; units of the active continental margin, olistostrom mélange, Sava-Vardar zone (*Internal Dinarides*). From the Oligocene general collision was typical together with several strike-slip structures, parallel with the extension of the Pannonian Basin (Tari 2002, Palinkaš et al. 2008). This extensional edge of the Internal Dinarides has a considerable geothermal potential, together with the buried continuation of the Dinaride basement in the basin (Bojadgieva 2008).

Most significant Prealpine deposits of the Dinarides are epithermal Fe-Cu-Sb-Hg-As-Au deposits related to Permian metarhyolites in the Mid-Bosnian Schist Mts. and Fe-barite-base metal replacement or mesothermal deposits mostly in Carboniferous flysch in Trgovska Gora and the Sana-Una Mts. The Triassic rifting and volcanism was associated with the formation of large sedex siderite-hematite (e.g. *Vareš*) and Pb-Zn-barite deposits (e.g. *Veovača*), and the large cinnabar (Hg) deposit of *Idrija*. In connection with the Alps, minor MVT Pb-Zn deposits also occur. Jurassic ophiolites contain podiform chromite and Cyprus-type Cu (-Ni) deposits. Lower Oligocene high-K, calc-alkaline volcanism induced Pb-Zn sulphide stockwork and vein type mineralisation at *Srebrenica*. Granitoid intrusions of the same period are surrounded by zoned polymetallic skarn deposits in the *Podrinje* region, where the most important metal is the antimony. Miocene volcanic phases were not fertile (Palinkaš et al. 2008, Palinkaš et al. 2016, Pamić & Jurković 1997).

## Mineralisations of the Balkans and the Hellenides

In the Cretaceous–Early Paleogene period the Northern part of the Balkan Peninsula was a zone of arc-type calc-alkaline volcanism in the continuation of the Southern Carpathians. After closure of the Vardar Ocean in the Paleogene a new subduction zone was formed in the Hellenides. Extensive tectonic regime evolved in the Aegean Sea, while the Balkan and Hellenides Range became a collisional zone (Richards 2015). Areas of high heat flow follow active plate boundaries: the Aegean Sea (the Hellenic Arc) and the Vardar and Struma lineaments bounding the Dinarides and the Balkans (Bojadgieva 2008).

Triassic intracontinental rifting-related magmatism produced VMS Cu-Pb-Zn deposits (e.g. in the Strandja and Gramatikovo ore districts), the stratiform iron ore of *Kremikovtsi* (which was later overprinted by polymetallic sulphide mineralisation) and some minor stratabound Cu-U deposits (Popov 2002). MVT Pb-Zn is hosted by Triassic carbonates of the Moesian Platform (Palinkaš et al. 2016). Paleozoic successions of the basins of the Moesian platform (Seghedi et al. 2005) and Serbia (Premović et al. 1988) contain several pyrite- and organic-rich black shale horizons. The Jurassic Vardar Ophiolite Complex hosts widespread, podiform chromite deposits and minor volcano-sedimentary Cu-Mn-P and sedimentary Fe occurrences. The Cretaceous collisional setting of the Pirin-Rhodope zone produced granite intrusions with attached Ni-Fe-Co-Cr laterites and oolitic Fe deposits (Popov 2002, Tsirambides & Filippidis 2012).

Paleogene volcanism has led to the development of two major metallogenic zones, both with an extended scale of deposit types, but mostly of moderate and small sizes. The ***Apuseni-Banat-Timok-Srednogorie zone*** (a synonym for the Banatitic Magmatic and Metallogenetic Belt) comprises of porphyry copper ( $\pm$ Au, Mo) (e.g. *Majdanpek*, *Assarel*, *Elatsite*) and massive sulphide (Cu,  $\pm$ Au) deposits (e.g. *Bor*, *Chelopech*) as most significant, associated with minor polymetallic skarn and sediment-hosted Au deposits (Popov 2002,



Jelenković et al. 2016). Hydrothermal Cu-Au and Pb-Zn-Au veins are typical in the Srednogorie (Popov 2002). The **Rhodope Massif** (with high-K volcanics) consists vein and replacement Pb-Zn-Ag deposits hosted by metamorphic rocks, low grade porphyry Cu-Mo associated with zoned epithermal polymetallic ores attached to dyke swarms, and sediment-hosted Au (Marchev et al. 2005). Volcano-sedimentary Mn-oxides also occur here (Tsirambides & Filippidis 2012).

Neogene volcanism of the Trans-Balkan belt produced further vein-type or metasomatic Pb-Zn-Ag (e.g. *Chalkidiki*) and Au(-Ag-Te) deposits, rare porphyry Cu and Mo also occur (Popov 2002). South from the Balkan Peninsula the volcanism from Late Oligocene to recent time of the Aegean Sea produced the ores of the **Attico-Cycladic ore belt**, hosting variable deposits similarly to the previous volcanic districts. Base and precious metal deposits occur in the Archipelago on Lavrion, South Evia, Mykonos, Tinos, Kythnos, Sifnos and Milos (Voudoris et al. 2014); epithermal polymetallic and Au deposits of *Milos* Island are significant (Alfieris et al. 2013). Milos is also a site of high geothermal potential in shallow setting (Tsakiris 2011).

### Brief assessment

The province is large and very variable from our point of view. The high mountains are collisional areas with low heat flux and uplifted basement, but there are subsiding basins with thinned lithosphere and high geothermal potential (like the Pannonian Basin) and recent or almost recent sites of magmatism, where the required temperature of a geothermal system can be reached at shallow levels.

Tethyan sedimentary successions host several ore bearing horizons, corresponding to anoxic events. Widely distributed stratiform and stratabound ores, like Permian evaporates with attached sulphide mineralisations (also known from the Variscan province), Triassic sedex Pb-Zn deposits or Jurassic black shales with Mn enrichments can be of considerable potential, mainly in deep setting of basin successions, or in the basement of Cenozoic basins.

Most promising targets for the CHPM project are those Cenozoic volcanic complexes, which host several volcanogenic deposits, mainly Sb and Hg in the Apennines and precious metal bearing Cu-Pb-Zn in the Carpathian-Balkan region. Known deposits are in elevated position, but the heat flow can be high enough even there for geothermal purposes, and as the volcanic mountains are mostly bounded by structures of subsidence, the existence of concealed deposits is a probable assumption. There are operating geothermal projects, which can be tested for metal extraction from the wastewater.

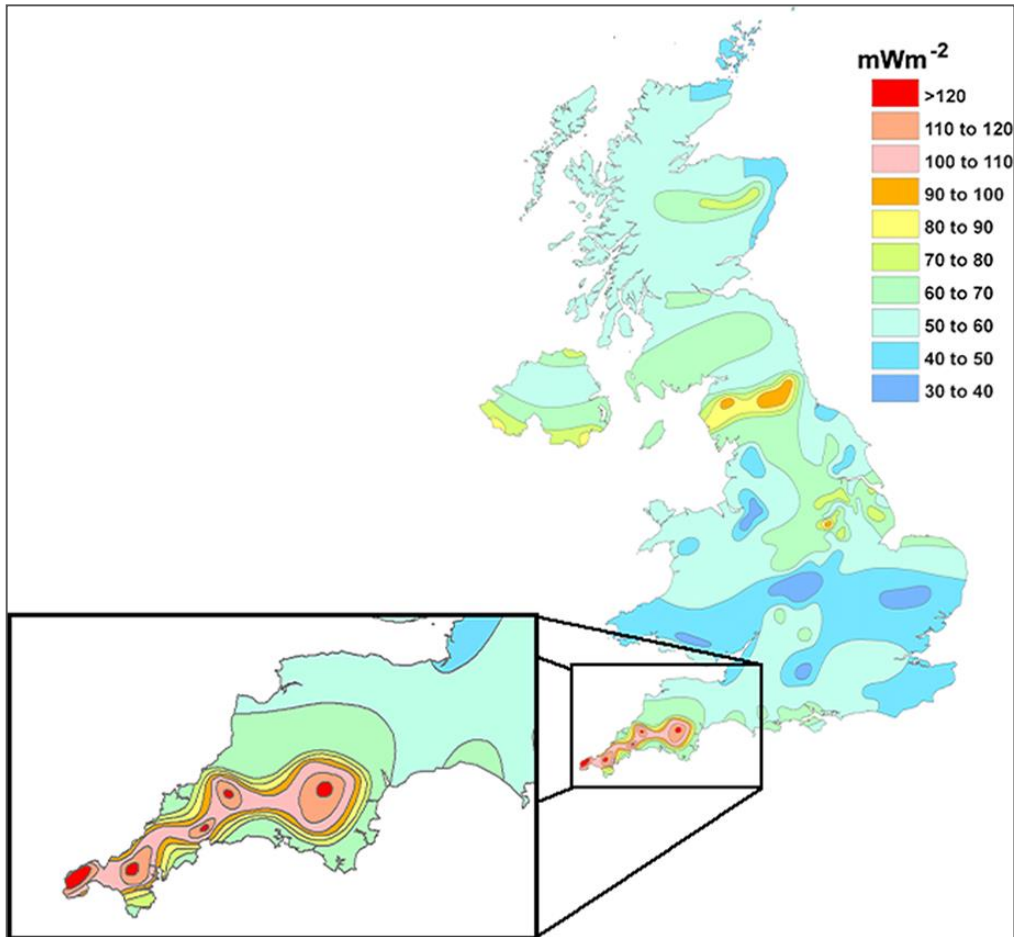
## 5.3 Project test areas

### 5.3.1 Cornubian Ore Field, England

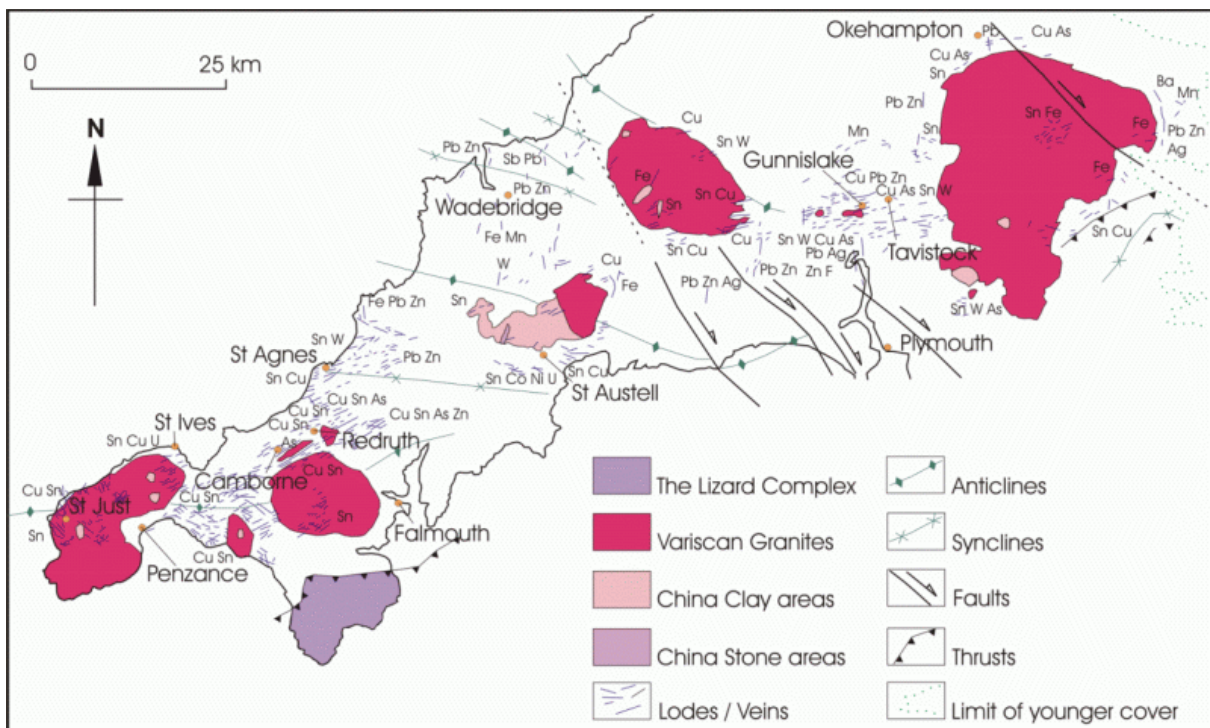
The high geothermal gradient areas in Great Britain are occurrences of granites enriched in radioactive elements located in Cornwall and in North England (Lake District and Weardale) (Figure 5.9). Actual values in Cornwall are estimated to 35–40°C/km (Downing & Gray 1985, Batchelor *et al.* 2010), confirmed by drilling down to 2500 m (Parker 1999).

This high heat production comes from a Variscan (270–295 MA old) S-type, ilmenite-series, two-mica monzogranite batholith (Willis-Richards & Jackson 1989). This intrusion formed the Cornubian Ore Field (Figure 5.10). Ore controls are subvertical faults and systematic joint sets either following or perpendicular to the strike of the elongate intrusive body. Three metallogenic phases are distinguished (Jackson et al. 1989):

1. Prebatholith stage (300–400 MA): stratabound Fe-Mn oxy-hydroxide, syngedimentary Fe, Cu
2. Synbatholith/main stage (270–300 MA): hydrothermal Sn-Cu-As-Fe-Zn-Pb sulphide lodes
3. Posbatholith stage (300–0 MA): epithermal Pb, Ag, Sb, Ba, Zn, Fe, U, Co, Ni, Au veins



**Figure 5.9** Heat flow map of the United Kingdom. URL: [www.bgs.ac.uk/research/energy/geothermal](http://www.bgs.ac.uk/research/energy/geothermal)



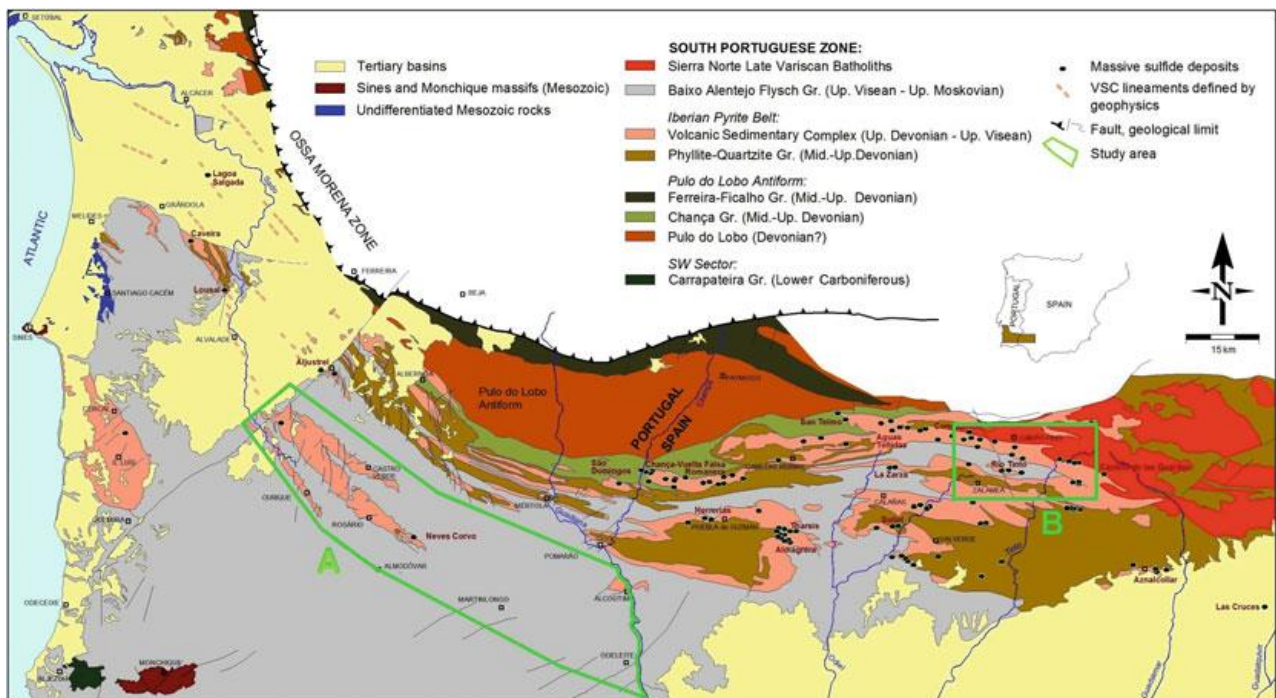
**Figure 5.10** Deposits of the Cornubian Ore Field (Dunham et al. 1978)  
 URL: [myweb.tiscali.co.uk/geologyofcornwall/Mineralisation.htm](http://myweb.tiscali.co.uk/geologyofcornwall/Mineralisation.htm) (2016-06-10)

The steep lodes are concentrated on the top of the batholith either in the granite or in the hornfels body of contacted Devonian sedimentary rocks. Sn, Cu, As are enriched in the proximal zone (<1500 m) and mostly in argillaceous host rock, while Zn, Pb and Ag was produced also further from the contact zone. The Western parts were richer in Sn, Cu and Zn than the Eastern side, which, in turn, was enriched in Fe, As, Sb, F and Ba, together with strong kaolinitization (Willis-Richards & Jackson 1989).

### 5.3.2 Iberian Pyrite Belt, Portugal and Spain

The W–E striking Iberian Pyrite Belt (IPB) lies in the Southwest part of the Iberian Peninsula, in a 240 km long zone between Grândola, Portugal and Seville, Spain (Figure 5.11). The area was mined since 5000 years; the main metals of the ores are iron, lead, zinc and copper, but several others are enriched too. The IPB is located in the South Portuguese Zone of the Variscan orogeny, at its Northern edge contacting the Ossa-Morena zone with the Aracena Metamorphic Belt, a suture marking the Variscan collision. The IPB itself suffered very low grade metamorphism only. The description of the IPB, when not indicated otherwise, is based on Leistel et al. (1998), Tornos et al. (2009) and Inverno et al. (2015).

The succession of the IPB indicates an intracontinental basin. The Middle-Upper Famennian Phyllite Quartzite Formation, underlying strata of the deposits, is a 2000 m thick siliciclastic shelf facies sediment. The host of the deposits, the 1300 m thick Upper Famennian – Upper Visean volcanosedimentary succession formed during the oblique collision. The volcanics are dominantly felsic and calc-alkaline, although basic dykes, sills and pillow lavas of variable geochemical character (Lescuyer et al. 1998) are also present. The stratigraphic cover is the Upper Visean Baixo Alentejo Flysch Group, comprising of Culm facies, turbiditic, synorogenic flysch sediments.



**Figure 5.11** Regional geology of the South Portuguese Zone, including the Iberian Pyrite Belt and associated VHMS deposits and showing location of the Neves Corvo (A) and Río Tinto (B) project areas (Inverno et al. 2015)

The typical ore structures are stratiform VMS deposits lying in polytict sediments, most often black shale over hydrothermally altered zones. Most common minerals are pyrite, sphalerite, galena and chalcopyrite. The

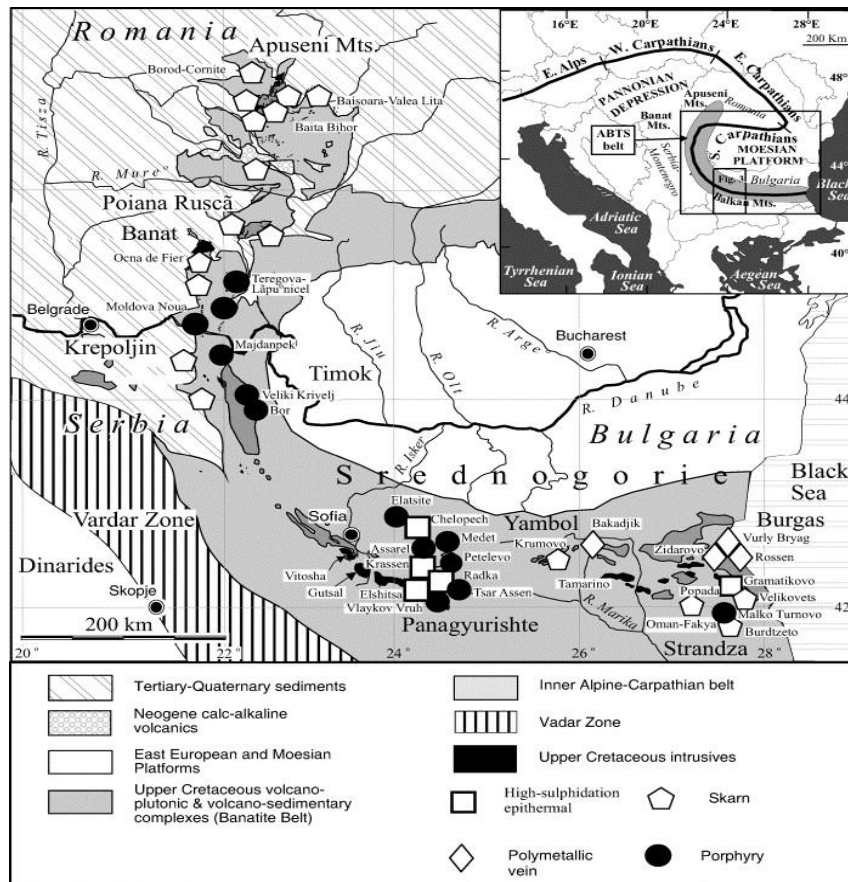
core of the alteration contains sulphide stockwerks and veins penetrating also the underlying phyllite, indicating the channel of the uprising brines over intrusive bodies. These zones contain Co- and Bi-sulphides and sulphosalts with Au and As-enrichments. The registered sulphide resources (mined + reserves) of the IPB are 14.6 Mt Cu, 13.0 Mt Pb, 34.9 Mt Zn, 46.1 kt Ag and 880 t Au, and that doesn't include the mines exploited for pyrite only. Typical grades for Cu are 0.5–1.5%. Neves-Corvo is exceptionally rich with 14.4% Cu and 1.6% Sn in its massive sulphide ore.

Three horizontal zones of the IPB can be distinguished. In the **Southern Zone** large pyrite rich exhalative deposits are hosted in slate of small marine basins typically. The giant deposits of Aznalcollar-Los Frailes, Sotiel Migollas, Masa Valverde, Tharsis, Neves-Corvo are located here with several smaller ones. The **Middle Zone** with two important deposits, La Zarza and Rio Tinto, shows transitional characteristics. The **Northern Zone** comprises mostly replacement ore deposits hosted in pumice-rich volcanoclastics. Deposits are usually smaller, but richer in base metals. This zone comprises mostly allochthonous thrust units, where identifying of the stratigraphical units is not as straightforward as in the Southern parautochthonous zone.

Two other ore types are present in the IPB. Chert and jasper beds intercalated in the Volcanosedimentary Complex contain high grade stratiform manganese ore, e.g. the Soloviejo deposit (Huelva) contains more than 175 kt Mn ore calculated with 35% Mn cutoff (Tornos et al. 2005). Some late-stage quartz and fluorite veins intrude the flysch with base metal sulphide or Sn-W ore minerals.

### 5.3.3 Banatitic Magmatic and Metallogenic Belt, Romania

The Banatitic Magmatic and Metallogenic Belt (BMMB) starts in the Southwestern part of Transylvania as a N–S striking zone, continued and arched to W–E in Serbia and Bulgaria. It comprises of calc-alkaline magmatic rocks of 92–72 MA ages, related to the subduction of the Vardar ocean basement beneath the European margin. Originally, the BMMB was a part of an E–W striking orogenic belt (Figure 5.11).



**Figure 5.12** The Apuseni–Banat–Timok–Srednogie Belt and its major deposits (Quadt et al. 2005)

The present-day shape can be attributed to subsequent Cenozoic deformation and rotation around the Moesian platform. Four different magmatic suites can be distinguished by geochemical character: a ‘normal’ calc-alkaline, a high-K calc-alkaline, a tholeiitic and a peralkaline suite. The latter ones are restricted to and mafic rocks are characteristic for the Eastern Srednogie (Ciobanu et al. 2002, Quadt et al. 2005, Berza & Ilinca 2014).

The main ore types of the BMMB are porphyry Cu-Mo-Au, HS epithermal Au-Ag and various skarn deposits. Typical reserves are 3–400 Mt for porphyry and 5–10 Mt for skarn deposits (Ciobanu et al. 2002). In the Romanian part, the Apuseni Mts. and the Poiana Rusca–Banat Mts. regions iron, copper and lead-zinc skarns are the predominant types. Skarn deposits host a wide range of ore minerals in a zoned pattern. The Cu-Mo skarn of *Baița Bihor*, for example, is also enriched in W and B. The zonation starts with Mo-rich proximal zone, then Mo-W-Bi-Te (in calcic skarns) or Cu-W-Bi (in magnesian skarns), then Pb-Zn zone (also veins around the skarn), finally a dedolomitization halo with B enrichment (Berza & Ilinca 2014).

The Eastern edge of the Pannonian Basin at the Apuseni Mts. is the most significant geothermal resource area of Romania. Existing wells exploiting mostly Triassic carbonate aquifers at 800–2400 m depth produce waters of 50–85°C (or 70–105°C at Oradea) at the wellhead (Rosca et al. 2015).

### 5.3.4 Bergslagen, Skellefte and Northern Norrbotten Mining Districts, Sweden

Three principal mining regions of Sweden will be introduced here based on the description made by the Geological Survey of Sweden. Bergslagen in the South and Skellefte in the North are situated in the Svecofennian Orogenic Belt, Northern Norrbotten (North from Skellefte) is in the Scandinavian Caledonides,

but still with Svecofennian formations. The magmatic host rocks of the major deposits are dated to 1.9–1.8 GA in all of the three regions.

The **Bergslagen** region comprises of Paleoproterozoic rocks. Ore deposits are associated with a calc-alkaline to alkaline volcanic and intrusive succession, and variable rock alterations, overprinted by amphibolite or greenschist facies metamorphism. The most important deposit types are: Fe oxide skarn or marble-hosted deposits (e.g. *Persberg ore field* and *Dannemora*, respectively), stratiform Mn oxide deposits spatially related to the Mn-poor skarns (e.g. *Långban*), quartz-rich iron oxide deposits including banded iron formation (e.g. *Striberg*), apatite-bearing Fe oxide deposits (e.g. *Grängesberg*), W oxide skarn deposits (e.g. *Yxsjöberg*), minor polymetallic and Mo sulphide deposits, and (as most significant) base-metal sulphide deposits rich in zinc, lead and silver. Two types of these can be distinguished: stratiform, Zn-Pb-Ag-rich and Fe-Cu-poor deposits (e.g. *Zinkgruvan*) and irregular, stratabound, massive and disseminated Zn-Pb-Ag-(Cu-Au) deposits (e.g. *Garpenberg* and *Falun*), both types hosted by rhyolitic metavolcanics. Three operating mines of the region are *Garpenberg* [Zn-Pb-Ag-(Cu-Au)], *Zinkgruvan* (Zn-Pb-Ag) and *Lovisagruvan* (Zn-Pb) (Stephens et al. 2009).

The **Skellefte** region was described as a Proterozoic volcanic arc with a low grade metamorphism. Dominantly felsic volcanics of the Skellefte Group and related intrusive rocks host the most important VMS type Cu, Zn-Cu or Zn-Cu-Pb deposits. Base metal grades are usually low ( $\text{Cu}+\text{Pb}+\text{Zn} < 10\%$ ), the largest deposits consist mainly of pyrite, but several of these are enriched in precious metal. At *Boliden*, *Holmtjärn* and *Petiknäs Norra* the Au content exceeds 5 g/t. Minor porphyry copper deposits are attached to granitoid intrusions, mainly of the Jörn Granitoid Complex. There are stratiform, replacement type Cu-Zn (chalcopyrite-sphalerite) ore bodies hosted by volcanoclastic-sedimentary formations mainly in the Adak area. In a WSW–ENE trending tectonic zone of the region several paragneiss-hosted, serpentized mafic and ultramafic intrusion were found with Ni enrichments ('Nickel zone'). Ni, Cu and PGE enrichments occur in massive sulphide lenses and a dissemination halo around these. Beyond these types, there are quartz veins with orogenic gold mineralisation controlled by fault zones crosscutting variable rock bodies. Later intrusions of the Transscandinavian Igneous Belt host Sn-W greisen and skarn deposits (Kathol & Weihed eds. 2005).

The **Northern Norrbotten** region has apatite rich volcano-sedimentary iron, stratiform copper and epigenetic copper-gold deposits. Iron ores are hosted by a series of Paleoproterozoic, calc-alkaline metavolcanics in various forms. The main ore minerals are magnetite and apatite, with enrichment of V and light REE (as monazite inclusions in apatite). The reserves of the large *Kirunavaara* deposit exceed 2000 Mt. The stratiform sulphide deposits (e.g. *Viscaria*) are hosted by the volcanoclastics, black shales and carbonates of the underlying Greenstone Group, together with minor skarn and BIF type iron deposits. Epigenetic sulphide ores occur mainly in veins and disseminated halos in both series and are Cu-dominated, in some cases with Au, while Pb-Zn enrichment is rare. The open-pit mine on the large *Aitik* deposit (*Gällivare* mining district) produces a pyrite-chalcopyrite ore of 0.4% Cu, 0.2 g/t Au and 4 g/t Ag (Bergman et al. 2001).

Data obtained from geothermal measurements were published for Skellefte and Northern Norrbotten, where heat flow values are cca. 50 mW/m<sup>2</sup> and the geothermal gradients are cca. 13–17 °C/km (Parasnis 1982).

## 6 Conclusions

The aim of this study is to provide an ore geological background for the development of the CHPM technology in Europe. Based on literature data, we have reviewed the ore forming processes and the metallogenic provinces of Europe, with a short assessment on the EGS potential of each metallogenic province.

There are several approaches for the classification of ore forming processes and ore deposits. During the characterisation of the deposit types, we followed Robb's (2005) system in which the focus is on the geological processes and the origin of mineralising fluids. We have put special emphasis on those deposit types which are relevant for the development of the CHPM technology: (1) deposits from magmatic-hydrothermal processes, (2) deposits from hydrothermal processes and (3) deposits from sedimentary processes.

The tectonic setting is in strong correlation with the ore forming processes and the distribution of metallogenic provinces. Taking this into consideration, we described four large metallogenic provinces within the EU: (1) Precambrian Fennoscandian Shield province, (2) Early Paleozoic Caledonian province, (3) Late Paleozoic Variscan province, (4) Mesozoic-Cenozoic Alpine province.

The Fennoscandian Shield province comprises almost exclusively Precambrian ore deposits, which underwent strong deformation and metamorphism; it is difficult to identify the original ore forming processes. Heat flow is generally low in the province but toward depths, the continuation of the deposits can be targets of EGS projects.

In the Caledonian province, the Alum Shale in Scandinavia can be a potential target. Experimental results indicate that several metals can be easily mobilised from this formation. As this area is characterised by low geothermal gradient, only the deeper extension of the formation is suitable for the CHPM technology. U-rich granitoid intrusions in Great Britain with vein-type base metal mineralisation, deep-seated North Central European areas of the Avalonia Terrains, and MVT deposits in Ireland can also be prospective.

The Variscan province provides a rich CHPM potential. The VMS deposits of the Iberian Pyrite Belt and the deep continuation of the Kupferschiefer are the best examples, but iron ores and black shales underlying the Carboniferous coal bearing sequences can also be target formations. High heat flow rates in the Cenozoic rift zones and magmatic provinces in France and Germany can promote the use of the widely distributed massive ore bodies and sulphide-enriched sedimentary horizons as prospective areas. Mineralised granite bodies with U enrichments have elevated heat flow rates. Such granite intrusions in Cornwall, in the Massif Central and in the Erzgebirge have also CHPM potential.

In the Alpine province, there is a large variety of ore deposit types. Widely distributed stratiform and stratabound deposits can be potential sites for CHPM. The best opportunities are provided by the Cenozoic volcanic complexes with base metal and precious metal mineralisations in the Carpathian-Balkan region. Although these deposits are in relatively high position, the elevated heat flow can be a favourable condition for the technology.

A general experience is that data regarding metal enrichments and ore minerals come from shallow depths of recent or ancient orogenic zones available for exploitation as solid ores. On the other hand, high geothermal potential is usually attached to extensional structures, basins or trenches covered by thick sedimentary successions, which were no targets of ore prospecting. However, there are a lot of hydrocarbon, water or geothermal exploration data on such areas. There is a potential for gaining

information in interpretation of the available data (e.g. drill logs) or in additional measurements (e.g. assaying of stored samples) for ore prospecting purposes with relatively low additional costs.

Beyond mineralised intrusive bodies and stratigraphic horizons of large horizontal distribution with examples mentioned above, there is a third important target type: the deep-rooted regional fault zones. These may host hydrothermal deposits remobilized from a hidden, deep fertile source, often with multiphase mineralisation overprints. When situated in active rift zones or on microplate boundaries, these are sites of elevated heat flow as well usually. Fault zones as controls of fluid movements can be regarded both as potential sites of mineralisation and of injecting and pumping. Geophysical data can predict the position of mineralised regions.



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