METALLOGENIC MINERAL PROVINCES AND WORLD CLASS ORE DEPOSITS IN EUROPE.

W. De Vos[1], M. J. Batista[2], A. Demetriades[3], M. Duris[4], J. Lexa,[5]
J. Lis[6], K. Marsina[5], and P.J. O'Connor[7]

[1]Geological Survey of Belgium, Brussels, Belgium
[2]Geological and Mining Institute of Portugal, Lisbon, Portugal
[3]Institute of Geology and Mineral Exploration, Athens, Greece
[4]Czech Geological Survey, Prague, Czech Republic
[5]Geological Survey of Slovak Republic, Bratislava, Slovak Republic
[6]Polish Geological Institute, Warszawa, Poland
[7]Geological Survey of Ireland, Dublin, Ireland

Introduction

Europe is rich in minerals, both metallic and industrial, and has an ancient tradition of mining and ore processing. Their impact on the geochemistry of the European environment is substantial, and is generally stronger for metallic than for industrial minerals. Some geological areas are richer than average in certain elements, and according to size they are called metallogenic provinces or districts. Also, some individual mineral deposits are so huge as to deserve world-class status. This section will examine some of the most striking examples of natural mineral wealth on the European continent.

Large Ore Deposits of Iron, Copper and Nickel in the Baltic Shield

In the Precambrian Fennoscandian Shield of north-eastern Europe, some exceptionally large ore deposits of iron, copper and nickel are found. Many of them are situated in a composite sulphidic ore belt running SE-NW through central Finland and into Sweden, including the Outokumpu region in the southeast, Pyhäsalmi in the centre, and the Swedish Skellefte district in the northwest. The metamorphic host rocks, of volcano-sedimentary origin, belong to the north Karelian schist belt, including gneiss, serpentinite, dolomite and skarn, with an average geological age of 1.9 billion years (Ga).

The Outokumpu deposit, discovered in 1910, is a high grade Cu deposit containing minor Co, Ni and Zn. The main ore minerals are pyrrhotite (23%), pyrite (21%), chalcopyrite (11%) and sphalerite (1.7%). The total amount of Cu metal, extracted and reserves, is about 1 Mt (million metric tonnes).

Just south of Outokumpu is the Kohtalahti Ni belt, striking SE to NW, with 150 000 tonnes of Ni metal, extracted + reserves.

Another major deposit is **Pyhäsalmi**, discovered in 1958, to the northwest of Outokumpu. It is a volcanic hosted massive sulphide deposit, the main minerals being pyrite, chalcopyrite, sphalerite and pyrrhotite. The total metal content exceeds 1 Mt and present reserves are more than 20 Mt of sulphides.

The **Skellefte** district in Sweden was also developed in the 20th century and includes the **Boliden** polymetallic deposit, which was once the richest Au-As deposit in Europe, producing also Cu, Ag, Pb and Zn. Several similar polymetallic deposits, although smaller, are mined at present. The combined cumulative gold production from these mines is in excess of 220 tonnes, sixty percent of which came from the Boliden deposit. Geologically, these ore bodies are related to quartz porphyry or other granitoid intrusions in a volcanic unit of dacitic to rhyolitic composition.

A second notable ore-producing zone in the Baltic shield is the **Kiruna** district in northern Sweden, in the late Archaean granite-greenstone terrane of the Karelian province. There are two mines in operation at present: Kiruna and Malmberget. The iron ore reserves of the Kiruna district have a total metal content of over 1 billion tonnes, and it is the most important iron producer in Europe at present. The ore minerals are mainly magnetite, with some hematite. Most deposits belong to the Archaean-type banded-iron formations (BIF), but some skarn iron ore occurs, and a few deposits contain either apatite (phosphate) or titanium oxide. The main orebody at Kiruna, composed of apatite-bearing magnetite, is roughly tabular, striking northeast and dipping about 60° to the SE, with a length of 4 km, an average width of 80 m and a depth estimated at 2 km. It is enclosed in a volcano-sedimentary complex of greenstone, conglomerate, phyllite, keratophyre and quartz keratophyre, intruded by several granodioritic porphyry dykes apparently related to the emplacement of the ore.

It is worth mentioning the **Kemi** chromite deposit in northern Finland near the Baltic sea, which was discovered in 1959. One of the rare large chromium deposits in Europe, its reserves are estimated at 30 Mt of ore with 26% chromite (Cr_2O_3). The ore is hosted by mafic-ultramafic intrusive rocks.

Polymetallic Deposits, Lead-Zinc Deposits in the Palaeozoic of Europe

Erzgebirge

The Erzgebirge is a major polymetallic mineral province in Europe, on the border between the Czech Republic and Germany (Saxony), with numerous hydrothermal mineral deposits associated with Variscan and younger granite intrusive bodies. There are many mines, some of historical importance, especially in the Middle Ages and the Renaissance.

Silver mining near Freiberg was described as early as 1168 AD, and continued until 1968 AD. More than 1000 polymetallic ore veins run through the crystalline basement in two roughly perpendicular systems, which are filled with a variety of sulphides, sulphosalts and native silver. The famous ore deposits of **Jáchymov** (Joachimsthal) show a similar mineral wealth. About 180 mineralised veins in micaschist and phyllite around a granite massif contain Ag, U and minor amounts of Bi, Co, Ni, Zn, Pb, Cu, Sb and As. The veins are rich in pitchblende, silver-bearing sulphoarsenides and native silver, along with other rare minerals and more common sulphides. The Jáchymov ore district was discovered in 1516 AD, and quickly developed into one of the largest mining centres of Europe. It attracted Agricola, who wrote a famous 16th century treatise on metals, mining and ore deposits ("*De re metallica*"), based largely on his observations at Jáchymov. The word '*dollar*' was derived from the German '*thaler*' which was a silver monetary unit named after Joachimsthal. At the end of the 19th century, radioactivity was studied intensively on Jáchymov uranium (U) ores, leading to the discovery of radium (Ra), and to the definition and understanding of radioactivity itself.

The **Pribram** area was mined for silver (Ag) from the 14th to the 16th century; from the 18th to the 20th century the polymetallic deposits were mined for Ag, Pb, Zn, Sb and Cu, and after 1940 uranium (U) was also recovered from the Pribram ores.

The **Cínovec** (Zinnwald) Sn-W-Li deposit consists of a regular vein system in greisenised zones of a granite body, containing the minerals quartz, wolframite, scheelite, cassiterite, zinnwaldite, topaz, fluorite, muscovite, Li-mica and feldspar. In the Altenberg deposit a large volume of the granite itself is greisenised and mineralised in tin (Sn) and tungsten (W).

Somewhat similar to the Erzgebirge, the **Harz Mountains** to its north harbour polymetallic deposits such as **Andreasberg**, **Rammelsberg** and **Bad Grund**, related to granitic intrusions in the Variscan orogenic belt. Total historic production of Rammelsberg alone is estimated at over 17 million tonnes of ore, mainly copper (Cu), lead (Pb) and zinc (Zn). Andreasberg was extremely rich in silver (Ag) and, together with the Erzgebirge district, accounted for three quarters of European silver production at the end of the Middle Ages.

Irish Base Metal Deposits (Zinc and Lead)

In recent years, Ireland has become a major Zn producer in Europe. The Lower Carboniferous carbonate rocks of Ireland are host to a large number of stratabound base metal deposits of variable sizes, mined both in the past and at present. Ore-forming processes in this distinctive metallogenic province may have been going on for a 50 million year time-span. Several orebodies are hosted in limestone and dolomite, known as Pale Beds, some in younger Waulsortian mudmount reefs, and a few in even younger beds, all belonging to the Lower Carboniferous. These rocks were deposited in shallow tropical seas about 370 to 350 million years ago. Part of the sulphides precipitated syngenetically in mud in the near-shore environment, but sulphide precipitation also occurred during diagenesis, dolomitisation and brecciation, partly related to a phase of volcanic activity in the final stages of carbonate deposition. Later, sulphides were deposited in veins, structurally controlled by Hercynian faulting. The probable metal source is the underlying basement, whereas most sulphur is supplied by bacterial reduction of seawater sulphate. The typical mineralogical association is sphalerite and galena with accessory pyrite and marcasite. Small amounts of silver are recovered from galena. Gangue minerals include calcite, dolomite, siderite and barite. Sulphides occur as carbonate replacement, sedimentary layers, disseminations, breccia/fracture infill, and as massive sulphides.

Recent exploration and research was encouraged by the discovery in 1970 of the **Navan** (Tara) deposit with ore reserves of 70 Mt grading on average 2% lead (Pb) and 10% zinc (Zn). The Tara mine has a potential output capacity of 170,000 tonnes a year of Zn concentrates and 42,000 tonnes a year of Pb concentrates. New Zn-Pb discoveries were made at **Galmoy** in 1986 and at **Lisheen** in 1990. The newly opened Lisheen mine, with 21 Mt reserves, is expected to produce 190,000 tonnes a year of Zn and 33,000 tonnes a year of Pb. Reserves at other deposits include 15 Mt at Silvermines, 10 Mt at Tynagh, and 7 Mt at Galmoy. The Irish metallogenic province has a total content of more than 14 million tonnes of extractable metals.

Silesian-Cracowian Zn-Pb Deposits of the Mississippi Valley Type (MVT)

The Upper Silesian ore district in south-central Poland is an important producer of zinc (Zn), lead (Pb) and silver (Ag), with mining going back at least to the eleventh century for silver and lead.

The stratabound deposits occur to the north and north-east of the Upper Silesian Coal Basin, where Permian to Mesozoic rocks lie monoclinally on a Variscan Palaeozoic substrate. The economic parts of the mineralisation occur mainly in the Muschelkalk series of the Middle Triassic, with ore bodies hosted by carbonate rocks, especially dolomites. The ore forms replacements, cavity fillings, linings, veins and mineralized breccias (Szuwarzyński, 1996). Recent production is from Zn-Pb sulphide ores hosted in a 200 m thick sequence of flat-lying shallow-marine Triassic carbonates, where the lower and upper units of the sequence enclosing the ores are marly or argillaceous sediments of lower permeability.

The main ore minerals include sphalerite, galena, pyrite and marcasite, accompanied by the gangue minerals dolomite, calcite, barite, chalcedony and quartz. Of secondary importance are lead-arsenic complex sulphides such as jordanite and gratonite. In part of the region Middle Triassic dolomites form outcrops, and zinc carbonates and rarer zinc silicates appear frequently in karst pockets (Przeniosło 2000; Szuwarzyński, 1996). Ores of the Silesian-Cracowian deposits concentrate Cd, Ag, Ge, Ga, As, Tl, Sb and Ni as isomorphic substitutions in sulphides or microinclusions (Kozłowski 1995). Mining activity developed in several areas around the towns Bytom, Tarnowskie Góry, Chrzanów and Olkusz.

The total extractable metal content of the district is estimated at 30 Mt. For the last twenty years, the mine production was 4 to 5 million tonnes of ores per year, including 140-250 thousand tons of zinc and 40-90 thousand tons of lead.

Zn-Pb Deposits in Southwestern Sardinia

The region of **Iglesiente-Sulcis** in SW Sardinia is an ancient mining district. Lead, silver and copper have been extracted since Roman times, followed later by zinc and barium. Mineralising processes were at work at different times through the Palaeozoic. The most important deposits are related to Cambrian carbonate platform sediments. The Sardinian mining district has produced about 15 Mt of metal, which makes it comparable to the Irish Province in metal content.

The Kupferschiefer in Poland

A major base metal district in Europe is south-western Poland, where a copper-bearing shale formation, the Kupferschiefer, occurs in the Permian. Stratigraphically it constitutes the boundary between the Rotliegendes or Lower Permian, and the Zechstein or Upper Permian. There are three layers mineralised with copper sulphides: the Weissliegendes or White Sandstone formation at the base, with decimetric to metric thickness; its upper portion contains 0.2 to 2% Cu in sulphides. Above it, the copper-bearing shale (Kupferschiefer) is the principal ore level, with 2 to 10% Cu content, and a thickness up to 20 m. The shale is usually bituminous, and always contains Cu, less frequently Pb and Zn sulphides. Carbonate rocks rest upon the copper-bearing shale; these contain Cu sulphides, and also small clay layers containing lead sulphides. The ore-bearing stratigraphic layers are mineralised in a reducing facies, which occurs in large patches, whereas in areas with oxidised facies in the same stratigraphic levels, ore is lacking. The largest mineralised area covers about 350 km² in the region around **Lubin**, **Rudna**, **Polkowice** and **Sieroszowice**, which are at present the main mining centres. The richest part of the Kupferschiefer is situated structurally in the Fore-Sudetic monocline to the NW of Wroclaw, extending from NW to SE and gently dipping (less than 12°) towards the northeast. Active mines reach a depth of 1200 m. The company Polska Miedź (Polish Copper), owner of the mines, produced 486,000 tonnes of copper in the year 2000, representing 3.3% of world copper production ; silver production was 1119 tonnes, and there is also some production of Pb, Au, Ni, Co and Mo. Industrial reserves are presently estimated at 780 Mt of ore with an average grade of 2% copper (Cu) and 40 to 80 g/tonne of silver (Ag).

The Iberian Pyrite Belt

The Iberian Pyrite Belt (IPB) is an arcuate belt, 250 km long and 25 to 70 km wide, in the southwest of the Iberian Peninsula. It belongs to the South Portuguese Zone, a major structural and palaeogeographic domain of the Iberian massif, and the most peripheral extension of the Hercynian orogen in Europe. The Volcano-Sedimentary Complex (Upper Devonian to Lower Carboniferous) hosts a large number of massive sulphide deposits, with over 1700 million tonnes (Mt) of sulphides, containing 14.6 Mt Cu, 13 Mt Pb, 34.9 Mt Zn, 46 thousand tonnes silver (Ag) and 880 tonnes gold (Au). These tonnages make the IPB one of the largest massive sulphide provinces of the world. More than 80 deposits are known, 8 of which contain more than 100 Mt of ore.

Mining in the area is very ancient. It started in the Chalcolithic Age (before 3000 BC), and continued through historical times, particularly in the Roman period. In the 19th century a large-scale and new intensive exploitation started, mainly in open pits like in the **Rio Tinto**, **Tharsis**, **La Zarza** and **S. Domingos** mines. Numerous deposits were traditionally mined for pyrite only, the polymetallic potential being recognized later. More than 50 mines are now closed, leaving behind unprotected open pits and significant areas occupied by mining tailings. In many cases acid rock drainage is observed with direct influence on streams and aquiferous waters.

The discovery in 1977 in Portugal of the concealed **Neves-Corvo** deposit, rich in Cu, Sn and Zn, led to renewed exploration and to new metallogenic research in the IPB, again leading to more discoveries. In the 90´s geophysical exploration led to the discovery of the Las Majadas, Castiellejitos, Las Cruces and Lagoa Salgada orebodies. **Las Cruces** and **Lagoa Salgada** are hosted in the Paleozoic basement below the Tertiary sedimentary basins of the Sado and Guadalquivir rivers respectively; both show a palaeo-gossan and a well-developed palaeo-supergene enrichment zone, with high-grade contents of Au and Ag.

At present six mines are in operation, five in Spain (Tharsis, **Sotiel-Migollas**, **Aguas Teñidas**, Rio Tinto and **Aznalcóllar**) and Neves-Corvo in Portugal, the latter being the largest single deposit in the IPB. Several other deposits are waiting to be developed, including the **Aljustrel** complex in Portugal as a potential producer of Zn, Cu, Pb and Ag.

The Volcano-Sedimentary Complex of the IPB has a thickness varying between 100 and 600 m. It is dated on the basis of its fauna and microfauna as Famennian (Upper Devonian) to Visean (Lower Carboniferous). Volcanism is bimodal, with basic rocks consisting of tholeitic lava, locally pillow lava, some alkaline lava and dolerite, whereas acidic rocks range from dacite to rhyolite. Different types of shale, black shale, siltstone, siliceous shale and chert occur in alternation with the volcanic rocks; shale is more abundant towards the top of the sequence.

The massive sulphide deposits have variable sizes and show different forms, from stockworks to stratiform massive mineralisation to disseminations. The ore bodies exhibit Hercynian folding along with the volcano-sedimentary sequences hosting them. Stockworks often seem to represent the feeder zones of the mineralising fluids. Hydrothermal alteration haloes generally accompany the massive sulphide emplacement, with chlorite and sericite as typical minerals, with a geochemical enrichment in Pb, Zn, Cu, Co, Sb, As, Sn, Bi, Ag, Se, Tl, Ba, and leaching of Na, Ca and immobile elements. Some ore bodies also contain Au. Gossans are often enriched in the same elements. Ore grades are generally between 0.5% and 1.5% Cu, with notable exceptions like Neves-Corvo (up to 14% Cu). Neves-Corvo also has a unique tin content of up to 12% Sn. Historically Zn grades are between 1.3% and 3.5%, and Pb grades mostly from 0.5% to 2%, with some exceptions, in one case even exceeding 20% Zn and 10% Pb. Silver generally reaches grades of 25 to 60 g/t, and gold, when present, varies between 0.3 and 3 g/t. The sulphur content is approximately 46%. Mineralogically pyrite is dominant, with chalcopyrite, sphalerite and galena the most common accompanying sulphides, and many accessory minerals.

It is difficult to talk about the Iberian peninsula without mentioning the world class mercury district of **Almadén** near Ciudad Real in south-central Spain. Red cinnabar and native mercury (Hg) occur in Silurian quartzite, partially intruded by basaltic lava and pyroclastics. The Almadén district produces 30% of the world mercury, and has the largest reserves, about 90,000 tonnes of Hg metal.

Also worth mentioning is the **Panasqueira** mine district in northern Portugal, one of the world's largest tungsten producers. Quartz veins linked to late Hercynian (Permian) granitic magmatism contain wolframite, cassiterite (Sn) and minor sulphides. Current production is in the order of 700 tonnes of WO_3 per year.

Antimony-Gold Deposits and Complex Sulphide-Siderite Ore Deposits in the Palaeozoic

Western Carpathians

The Low Tatra and Little Carpathian mountain ranges of the **Western Carpathians** (Slovak Republic) are well known for their Sb-Au deposits (with antimonite, pyrite and arsenopyrite as the main ore minerals) hosted in granitoids and migmatites of the Hercynian basement. Historical mining lasted here for centuries and stopped in the early nineties of the 20th century. Up to 1.5 million tons of Sb ore (1.5 to 5% Sb, 1 to 3 g/t Au) were exploited and processed in the **Dúbrava-Magurka** and **Pezinok** ore districts.

The metamorphosed Early Palaeozoic volcano-sedimentary complex of the Spišsko-gemerské rudohorie mountain range harbours an extensive ore district with VMS copper (**Smolník**), replacement siderite (**Nižná Slaná, Železník**), magnesite (**Jelšava – Dúbrava, Košice**), vein type siderite/sulphide (**Rudňany, Slovinky, Gelnica, Rožňava** with siderite, barite, pyrite, chalcopyrite and tetrahedrite as the major ore minerals) and vein type Sb-Au (antimonite - **Čučma, Poproč**) deposits. According to a rough estimate 15 kt Sb, 500 kt Cu and 45 Mt Fe has been produced in the district until the end of the 20th century.

Tertiary Carbonate Hosted Deposits

Among the world class deposits is also the **Lavrion** or Laurium massive sulphide ore district in Greece, which lies to the southeast of Athens, with a total production of about 43 Mt of ore. The mineralised zone has a N-S to NNE-SSW trend, and is approximately 17 km long and at least 6 km wide. The ore occurs at the contact of marble and schist, and is classified as a carbonate-hosted replacement massive sulphide type. The main ore minerals are argentiferous galena, sphalerite, pyrite, chalcopyrite and arsenopyrite. Lavrion is a mineralogist's paradise: more than 265 minerals have been recognised (Marinos and Petrascheck 1956, Gelaude *et al.* 1996, Lapis 1999).

The ancient Greeks mined from the 7th to the 1st century BC about 13 Mt of ore with an average grade of 20% lead (Pb) and 400 g/t silver (Ag); the extracted metal was estimated to be about 1.4 Mt lead and 3500 tonnes silver (Conophagos, 1980). More recent exploitation, from 1865 to 1977 AD, mined about 30 Mt of ore with an average grade of 3% lead and 140 g/t silver; the extracted metal was approximately 0.9 Mt lead and 4,200 tonnes silver.

Tertiary Volcanic Hosted Deposits

Volcanic hosted precious and base metal deposits of the Western Carpathians

Neogene volcano-plutonic complexes host porhyry, skarn, replacement and epithermal mineralisations. The **Banská Štiavnica** ore district with epithermal veins in an area of 100 km^2 represents one of the richest mining districts in Europe. Galena, sphalerite, chalcopyrite and pyrite are the major ore minerals. Roughly 80 tons of gold, 4,000 tonnes of silver, 70,000 tonnes of Zn, 55,000 tonnes of Pb and 8,000 tonnes of Cu have been produced during one thousand years of mining.

The **Kremnica** epithermal gold deposit has produced around 20 t gold since the 12th century and the same amount of gold is available in reserves of the planned open pit operation.

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