ROBOMINERS DELIVERABLE 5.1

REVIEW DOCUMENT GIVING SCOPE AND EXAMPLES OF DEPOSIT TYPES OF INTEREST

Summary:
This document provides a review of ore deposit types and their characteristics relevant to the robominers technology. The description of the mining scenarios and a summary of the potential application of the technology in Europe is also provided.

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1 EXECUTIVE SUMMARY

In the provisioned robominers technology, an autonomous, fully functional, modular robotic miner would exploit mineral deposits, which are not economic for traditional mining. The aim of the recent study is to review the geological conditions at which the technology is applicable.

Based on detailed literature research, the main characteristics of the ore deposit types are discussed in a genetic system, and the most important European examples are described for each deposit type. Special emphasis is put on the features that make the given mineralisation type suitable for robotic exploitation.

The usability of ore deposit types for such mining robots is examined from different aspects, such as market demand, basic geotechnical conditions and the environmental effects of refining metals. The technology requirements for the different kinds of deposits are summarised in a separate section. Three potential geological and mining scenarios are identified, and a specific mineralisation for each scenario is characterised with relevancy to the applicability of these robominers.

With a European outlook, the most important ore deposits of Europe are shortly characterised, while placed in the main metallogenic provinces of the continent.

The deliverable provides input for ongoing and later work phases like simulations and virtual prototyping. The results are also considered during the design of the selective mining perception and production tools, the development of the mining robot, and the system integration.

2 INTRODUCTION

2.1 Objectives of the ROBOMINERS project

The natural resource management industries are relatively slow to react with continuous innovations to the ever-changing needs of societies for mineral raw materials, fossil energy, water etc. The main reason is the difficulty of working in harsh environment (elevated temperature, gases, water, etc.), imperfectly known ground conditions, difficulty in selecting the ore minerals from waste, and the mining environment, which is seldom standardised, and holds unique features which can not be approached by model simulations.

The overall strategic objective of the ROBOMINERS project is to enable EU access to strategic mineral raw materials from domestic resources. In order to reach this goal, the project aims to develop a bio-inspired, modular and reconfigurable robot-miner for mineral deposits, which are not economic for exploitation by traditional mining. A fully functional modular robot miner prototype is being designed, which is capable of operating, navigating and performing selective mining in a flooded underground environment. A mining ecosystem of expected future upstream/downstream raw materials processes will also be designed via simulations, modelling and virtual prototyping. The key functions of the robot-miner will be validated to a level of TRL-4. The prototypes will be used to study and advance future research challenges concerning scalability, resilience, re-configurability, self-repair, collective behaviour, operation in harsh environments, selective mining, and production methods as well as for the necessary converging technologies on an overall mining ecosystem level.

The robominers technology will not be a robotic extraction machine alone, instead, the whole production cycle should undergo serious modifications, creating not only an upgraded variety of old established technologies, but a revolutionary new approach. It may be a powerful tool of the resource management industries of tomorrow or even in the more distant future in a narrow segment of mineral raw materials.

2.2 Scope and structure of Work Package 5

The ROBOMINERS project consist of twelve work packages. The aim of Work Package 5 – 'Enabling geoscience' is to review mineral deposit types, their origin and occurrence, in particular those that are well known, but considered uneconomic because they are too small, too deep or difficult to access. Deposits are selected that could become desirable targets for the robominers technology, with full understanding of geotechnical, rock-mechanical, mining engineering and mineral exploration challenges of their exploitation. A comprehensive checklist is created and geo-parameters are described that will be required for setting up the deposit and mining simulations in Work Package 2.

Work Package 5 includes four tasks. Task 5.1 involves literature research on mineral deposit types and the potential mining scenarios for the technology. Task 5.2 focuses on the rock-mechanical, geotechnical and chemical characterisation of the deposit types that will affect the stability of the mining environment. Task 5.3 includes research on publicly available data at national level on mineral deposits, which are potential targets of the developed robotic mining technology in almost 20 countries. Task 1.4 provides a stock of engineering processes and technology solutions that are available from various sub-sectors of the extractive industries.

2.3 Relation to later work phases and structure of this deliverable

This deliverable was prepared in the frame of Task 5.1. The aim of this study is to summarise the potential geological situations for the optimal hosting of the robominers technology, and to assess the key input parameters for upscaling onto a possible engineering design of the system components. The potential deposit types are investigated in the light of the special constraints imposed by the innovative manless technology.

The deliverable provides input for the simulations and virtual prototyping, as well as the designing of the selective mining perception and production tools. The results of the study are also considered during the design and development of the mining robot.

Deliverable 5.1 is structured in ten chapters.

In Chapter 1, a short summary of this deliverable is provided.

Chapter 2 is an introductory part. Here, the objectives of the ROBOMINERS project are outlined, as well as the structure of Work Package 5, within which the recent deliverable has been prepared.

Chapter 3 is a short review of the main ore forming geological processes.

Chapter 4 includes the description of the ore deposit types in a genetic system, their formation and the main characteristics relevant for the robominers technology. More details are given on those deposit types, which are relevant for the application of the robominers technology, and the most important European examples are mentioned for each deposit type. A ranking of the deposit types based on their usability for the technology is also provided.

Chapter 5 applies a geometric approach. Ore deposits are discussed in a dimensional system and their forms and extensions are characterised.

Chapter 6 reviews the suitability of ore deposits for the robominers technology and the main technology requirements for the different deposit types.

Chapter 7 describes the possible geological and mining scenarios for the robominers technology providing a detailed characterisation of a typical example deposit for each scenario.

In Chapter 8, the main metallogenic provinces of Europe are characterised with a special focus on the relevancy for the robominers technology in each metallogenic province.

Chapter 9 is a synthesis of the outcomes from the former chapters.

Chapter 10 provides a list of references in which the bibliography used for preparing the recent study is listed.

3 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. 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. In the recent study, we consider ore as a rock material from which metallic components of economic value can be extracted.

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 given zone. 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 rock 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).

The spatial distribution of ore deposits strongly correlates with the tectonic setting. 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).

4 CLASSIFICATION OF ORE DEPOSITS

There are many different approaches and ways for the classification of ore 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, ad 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 (magmatic), (2) hydrothermal and (3) sedimentary processes and deposits.

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. Magmatic deposits
2. Magmatic-hydrothermal deposits
3. Hydrothermal deposits
4. Sedimentary deposits

As they have no relevancy for the robominers technology, we do not consider the deposits by surficial or supergene processes.

4.1 Magmatic deposits

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 magmatic origin have a larger variety *(Figure 1).*

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 calcophile elements like Fe, Cr, Pt, Ni, Cu 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 (like 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 partial melting, crystal fractionation and liquid immiscibility.

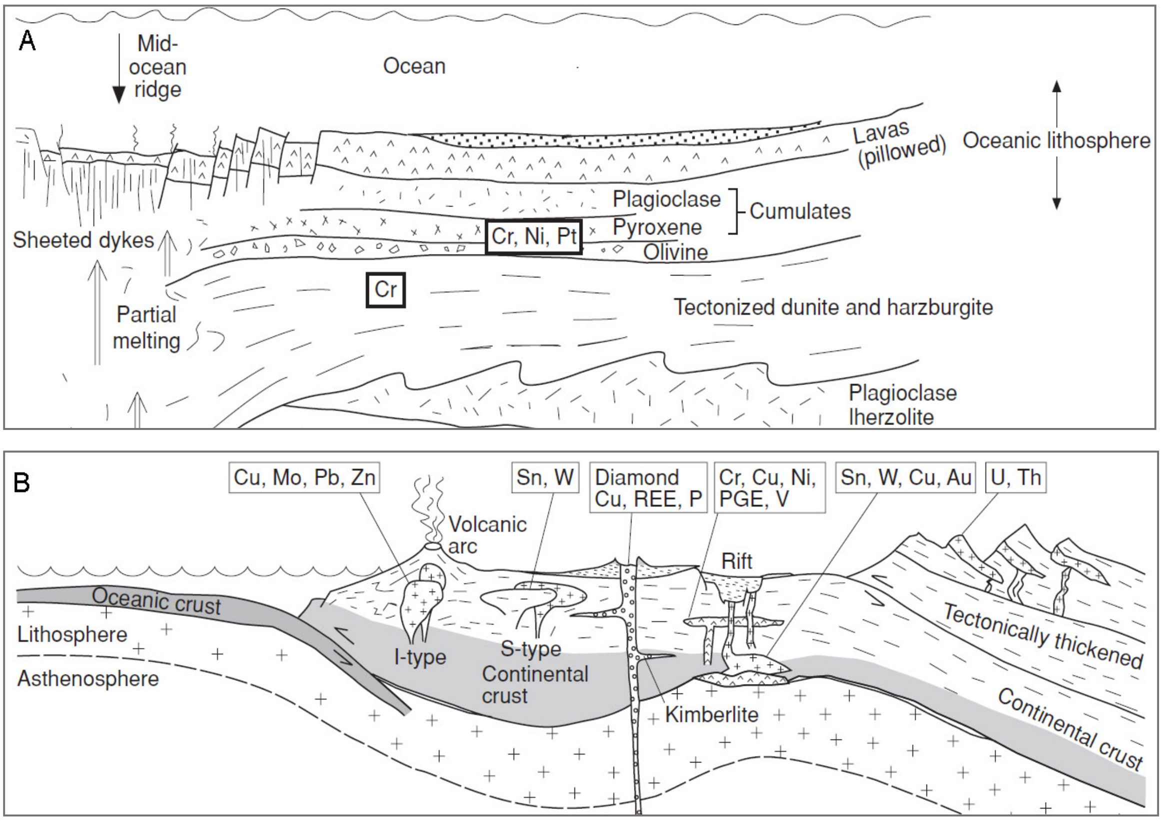


Figure 1: Oceanic (A) and continental (B) architectures with the main types of characteristic igneous related ore deposits. Source: Robb, 2005

Within the magmatic group, the following deposit types are shortly characterised:

- Orthomagmatic Cr-Fe-Ti deposits,
- Orthomagmatic Cu-Ni-Fe-Pt deposits,
- Carbonatite-alkaline intrusion related deposits.

4.1.1 Orthomagmatic Cr-Fe-Ti-V deposits

These deposits are found almost exclusively in association with basic and ultrabasic plutonic igneous rocks. The ore occurs in layered mafic-ultramafic intrusions, which usually have a well defined and predictable structure that can contain multiple ore bearing horizons. These horizons are 0.5–1 meter thick and extend laterally for tens of kilometres *(Figures 2, 3)*.

There are many mafic intrusions that contain layers of almost monomineralic chromite or magnetite (with titanium and vanadium). 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 pause only the single oxide phase is formed (Irvine 1977). The separation of crystal phases from residual melt is generally explained by gravitational segregation.

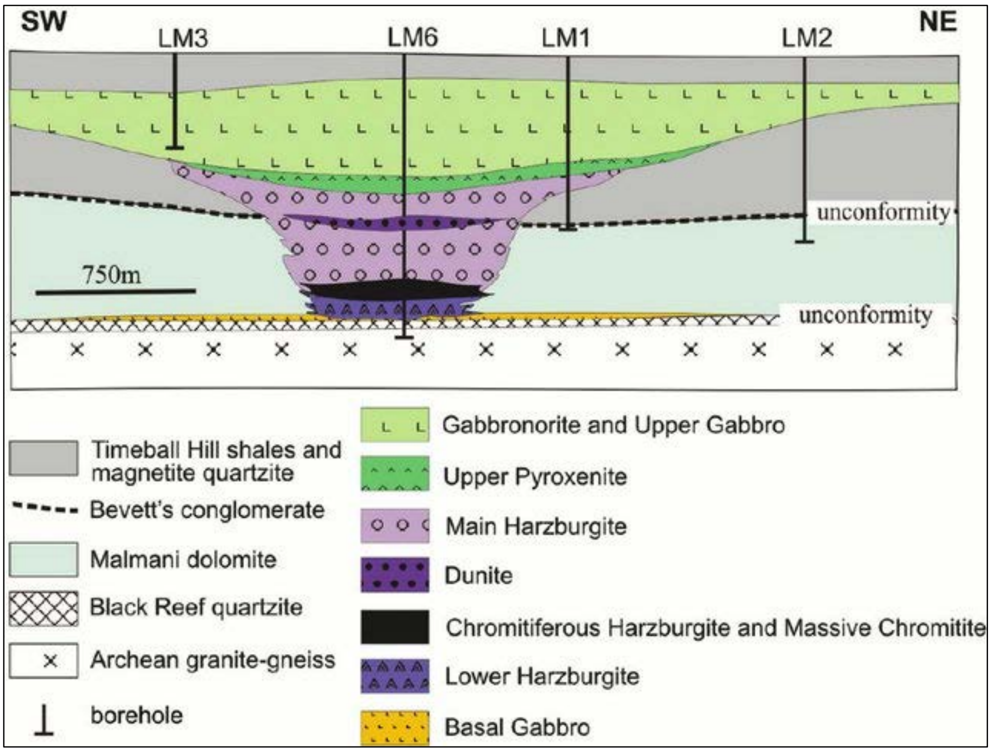


Figure 2: Geological cross-section of the Uitkomst Complex, South Africa. Source: Yudovskaya et al., 2015

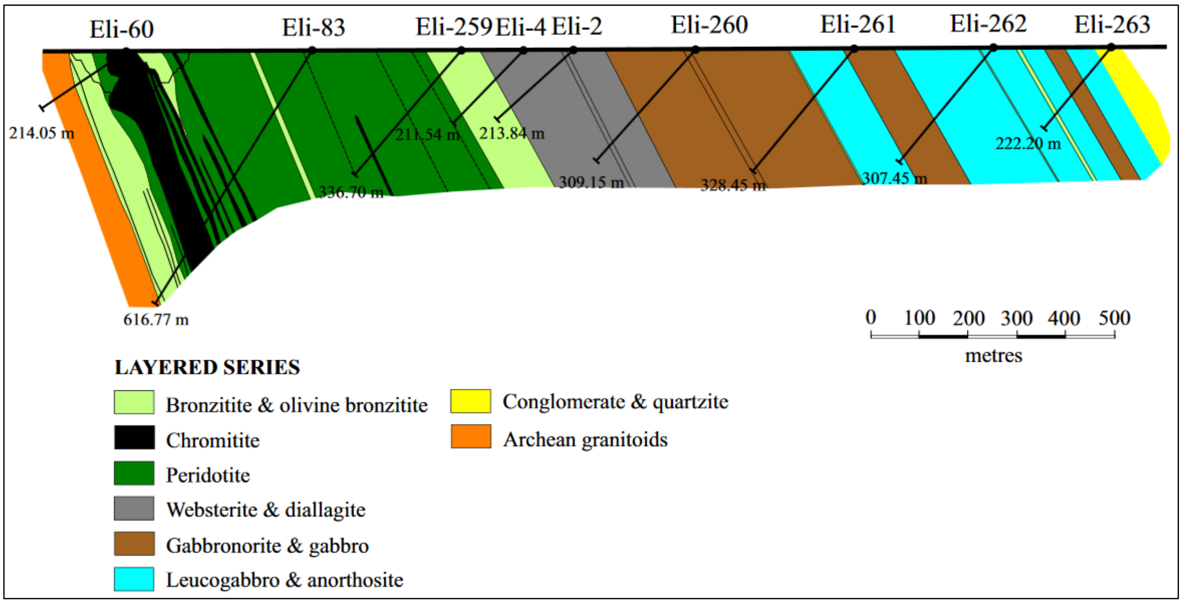


Figure 3: Cross-section of the Kemi intrusion (Finland) based on diamond drilling. Source: Rasilainen et al., 2016

Although the giant Cr deposits form extensive layers, chromitite can also appear in podiform structures. Podiform Cr deposits are usually comprised of small, irregularly folded, and dislocated pods that are lenticular in shape (Figure 4). 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. 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).

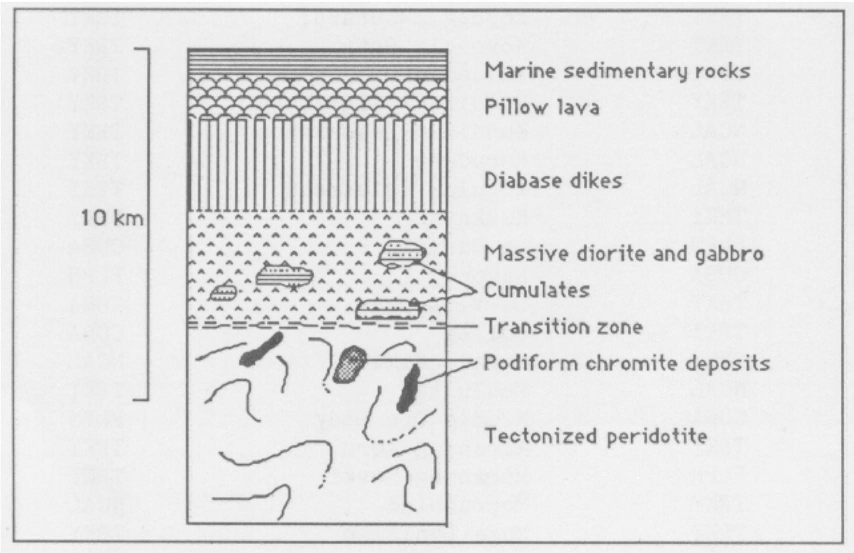


Figure 4: Cross-section of a typical ophiolite sequence showing locations of podiform chromite deposits. Source: Dickey, 1975

Within Europe, podiform ores occur in Finland, Turkey, Cyprus and Albania.

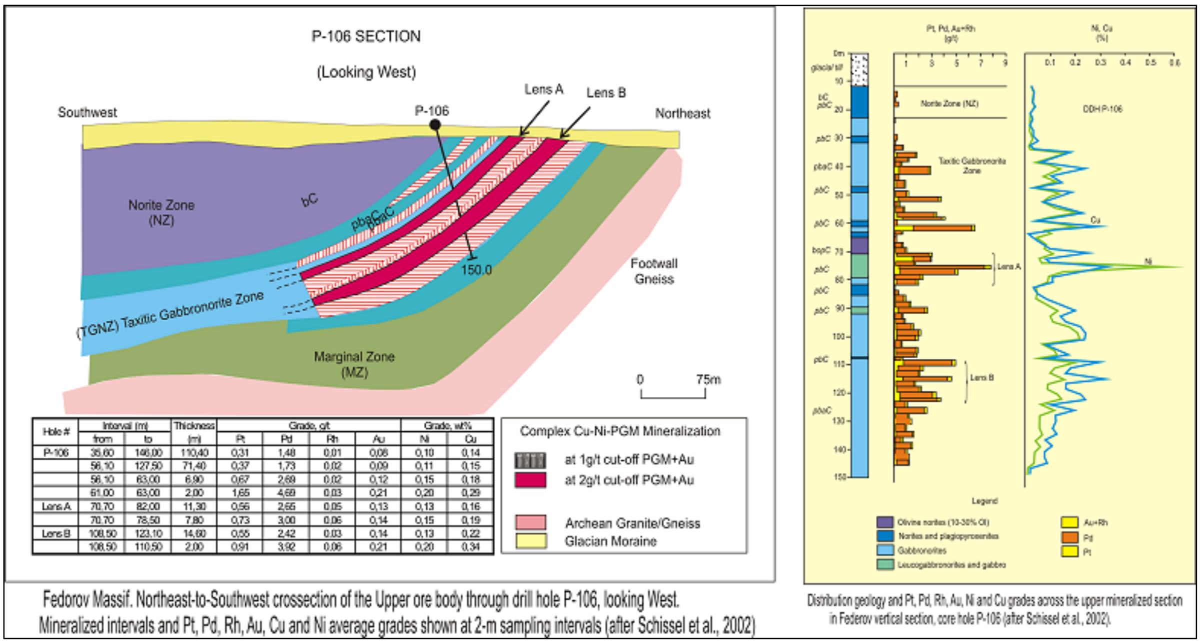
Bushveld-style chromite-bearing reefs generally have sharply defined footwalls and hangingwalls. Robominers technology is ideally suited to exploitation of such deposits, especially those which are thinner than can profitably be exploited by conventional mining.

Substantial podiform chromitite deposits are also found at Chromtau, Kazakhstan. Although the structures are well defined, the margins are often gradational, with the Cr content becoming progressively lower away from the ore body, and the use of robominers methods would in such cases be dependent upon reliable analysis of extracted material and real-time grade estimation to define a mining cutoff.

4.1.2 Orthomagmatic Cu-Ni-Fe-Pt deposits

These deposits are related to mafic-ultramafic magmas and formed by liquid immiscibility, which means the segregation of two coexisting liquid fractions from an originally homogeneous magma. Silicate-sulphide immiscibility can lead to the formation of giant deposits such as the PGE sulphide 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).

The sulphide ore generally occur in form of extensive, tabular or lens-like structures at the base of the magmatic body. The ore minerals can also be present in dissemination, forming lower grade parts of the deposit. There are no significant Cu-Ni-PGE deposits in Europe. Cu-Ni-PGE-Au ore is mined in the Keivitsa-Satovaara layered complex in Finland. The komatiite-hosted Sakatti deposit is also a promising occurrence. Major Bushveld-style Cu-Ni-PGE deposits occur in the Pana/Fedorova mafic/ultramafic complex in the centre of the Kola Peninsula, Russia *(Figure 5).*



Hole #	Interval (m) from	Interval (m) to	Thickness (m)	Grade, g/t Pt	Grade, g/t Pd	Grade, g/t Rh	Grade, g/t Au	Grade, wt% Ni	Grade, wt% Cu
P-106	35,60	146,00	110,40	0,31	1,48	0,01	0,06	0,10	0,14
	56,10	127,50	71,40	0,37	1,73	0,02	0,09	0,11	0,15
	56,10	63,00	6,90	0,67	2,69	0,02	0,12	0,15	0,18
	61,00	63,00	2,00	1,65	4,69	0,03	0,21	0,20	0,29
Lens A	70,70	82,00	11,30	0,56	2,65	0,05	0,13	0,13	0,16
	70,70	78,50	7,80	0,73	3,00	0,06	0,14	0,15	0,19
Lens B	108,50	123,10	14,60	0,55	2,42	0,03	0,14	0,13	0,22
	108,50	110,50	2,00	0,91	3,92	0,06	0,21	0,20	0,34

Figure 5: Section through the Fedorova layered PGM deposit, Kola Peninsula

PGM-bearing reefs, often containing complex cobalt, nickel, and copper minerals (sulphides, tellurides, and bismuthides) would also be amenable to exploitation by robominers methods, though the extraction of concentrates of the PGMs may well be a complex process, with initial simple gravity separation by the robominers equipment, followed by flotation, roasting, and other methods at surface. A significant complication for conventional mining of these particular deposits is the 40-45 degrees dip angle, which is equally inconvenient for both traditional seam mining methods and extraction of steeply dipping vein deposits, but could be handled well by robotic mining methods.

4.1.3 Carbonatite-alkaline intrusion related deposits

Alkaline magmatic rocks are generally small in volume in comparison with calc-alkaline magmatism, but they can have a large range in composition. Mineral deposits that form in the alkaline intrusion related mineral system are also quite diverse, including diamond, REE, P, U, Ni, Cu, PGE and vermiculite deposits. Moreover, these deposits contain a large number of critical commodities.

Carbonatites are igneous rocks with more than 50% modal carbonate. They occur related to alkaline intrusions. Mineralisation is commonly restricted to carbonatite dykes, sills, breccias, sheets, veins, and large masses, but may occur in other rocks associated with the complex rocks. Carbonatite is the main host rock of REE mineralisations. The main REE-bearing (Ce) mineral is monazite. The world's largest REE resource is the Bayan Obo Fe-REE-Nb deposit in Inner Mongolia, China.

The REE-bearing carbonatite occurs in vein-like structures and dykes. In the significant deposits, the thickness of the dykes can be a few hundreds of meters *(Figure 6).*

In Europe, the most important carbonatite-alkaline related ore deposit can be found in the Kovdor alkaline and carbonatite province, Kola Peninsula. From the ore complex, phosphate, Fe, and REE are produced. Carbonatite related REE mineralisations also occur in Greenland, Finland, Sweden, Norway and Ukraine.

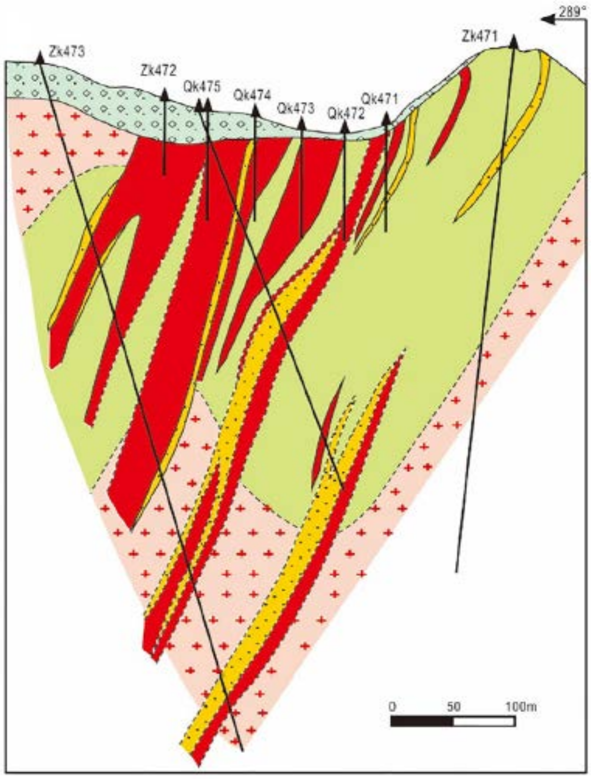


Figure 6: Cross-section of the Maoniuping REE deposit, eastern Tibetan Plateau, showing the distribution of REE-bearing carbonatite orebodies (red) and barite veins (yellow) in alkaline igneous complex. The extension of the carbonatite dykes reaches 1400 m in length and 350 m in width. Source: Zheng & Liu, 2019

An important carbonatite deposit is found at Sokli, in East Lapland, Finland (not far from Kovdor). This deposit is characterised by containing a large proportion of phosphate and magnetite (similar to Kovdor) but also significant deposits of Nb and veins of REE. These would be readily amenable to robomners extraction because the contacts tend to be well defined, and with strongly contrasting chemistry of the different geological units.

4.2 Magmatic-hydrothermal deposits

Magmatic-hydrothermal processes cover transport and precipitation from juvenile water emitted from the rock 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 amphiboles, biotite, chlorite, clay minerals and serpentine. 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).

Boiling is resulted in 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 sulphur content of the magma, light metals like lithium or beryllium and incompatible elements fractionate into the volatile phases. Chalcophyle elements (e.g. Pb, Zn, Cu, Sb) 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).

Magmatic-hydrothermal deposits include the following deposit types:

- Pegmatite deposits,
- Greisen deposits,
- Porphyry and epithermal deposits,
- Skarn deposits.

4.2.1 Pegmatite deposits

Pegmatites are very coarse-grained rocks derived from magma that may have crystallized in the presence of 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, Zr and REE (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 small vein-like structured or patches (a few tens of centimetres in diameter) in parent granites to 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) *(Figures 7, 8).*

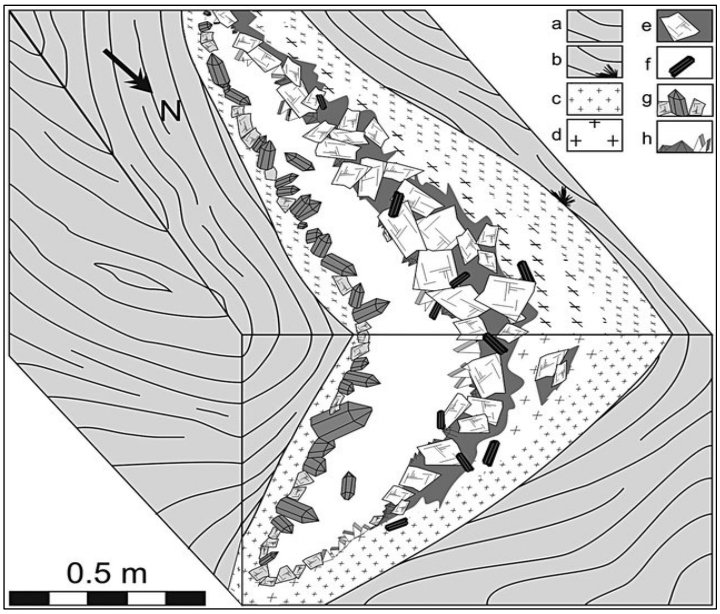


Figure 7: Idealised cross-section through a common pegmatite with pockets from Znětínek, Czech Republik. a) Host migmatised biotite-sillimanite gneiss, b) tourmaline on the contact, c) medium-to coarse-grained granitic unit, d) graphic unit, e) blocky K-feldspar with massive quartz (grey), f) tourmaline (black), g) large crystals of smoky quartz + albite + muscovite
Source: Gadas et al., 2012

The origin of pegmatites is explained as products of extreme crystal fractionation of mainly granitic magmas. The transition from granite to pegmatite marks the point at which H2O fluid saturation occurred in the crystallization sequence and therefore pegmatites, formed in the presence of an immiscible H2O + volatile fraction. The most giant pegmatitic deposits are Bancroft in Ontario, Canada, the Rössing uranium deposit in Namibia and the Bikita pegmatite in Zimbabwe.

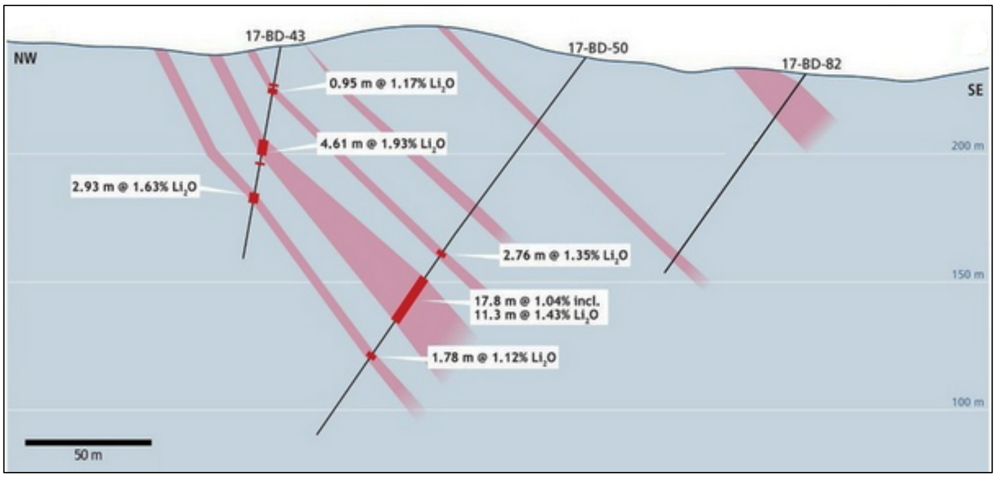


Figure 8: Cross-section of a part of the Carolina Tin-Spodumene Belt, North Carolina, US. Li is concentrated in parallel pegmatitic veins up to 16 m in thickness. Source: https://www.prnewswire.com/news-releases/four-kilometers-of-mineralisation-confirmed-at-the-piedmont-lithium-project-300526482.html

In Europe, there are several less significant pegmatite deposits. Examples are the scandium pegmatites in Baveno, Italy and in Tørdal, Norway; the Cornwall pegmatites in SW-England; the Li-Nb-Ta pegmatites in Dobra Voda and Rozna, Czech Republic and in Hagendorf, Germany; or the Th and REE-bearing pegmatites in Ytterby, Sweden. Pegmatitic deposits are preferable targets of the robominer technology because of their geometry and size. However, the host rock is very hard (generally granite) which makes the extraction difficult.

4.2.2 Greisen deposits

Greisenisation is a rock alteration specific to the cupola zones of granites. Greisen ores contain Sn and W mineralisation, as well as significant concentrations of other incompatible elements such as F, Li, and B. It is a granoblastic (equigranular texture in which crystals adopt a polygonal morphology with grain triple junctions) 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 (*Figure 9*).

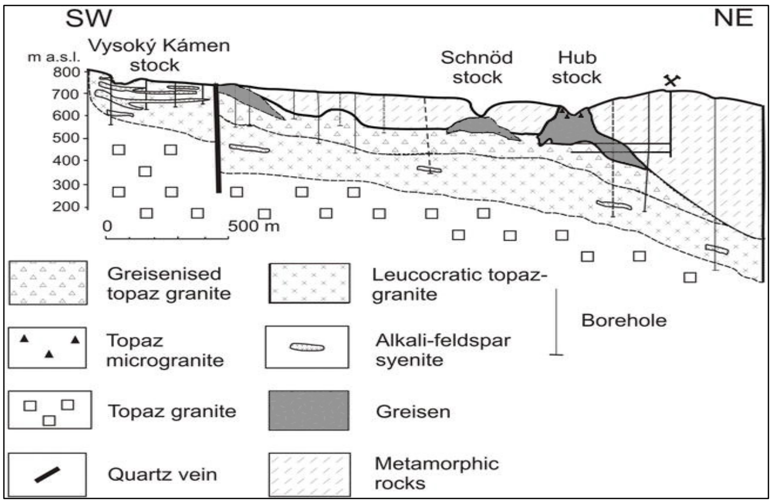


Figure 9: Schematic cross section of the southeastern part of the Krudum granite body, Krásno–Horní Slavkov ore district, Czech Republic. Source: René, 2017

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

Greisen deposits may be suitable for the robominers technology as the ore minerals occur in well identifiable sheet-like or irregular bodies, but he hard character of the hosting granite may raise difficulties. However, greisenised granite is often also subject to other alteration such as kaolinisation, which can make fragmentation much simpler. For robominers, this need not be a problem, though separation of a concentrate may require processing methods that work well with average grain sizes of millimetres upwards.

4.2.3 Porphyry deposits

Porphyry ore systems originate from the metasomatism (chemical rock alteration and replacement of minerals) by high temperature magmatic fluids exsolved from an intrusion. The name 'porphyry' refers to the typical texture, which means that sulphide crystals are disseminated in the rock mass. However, stockworks and tiny veins are also common forms.

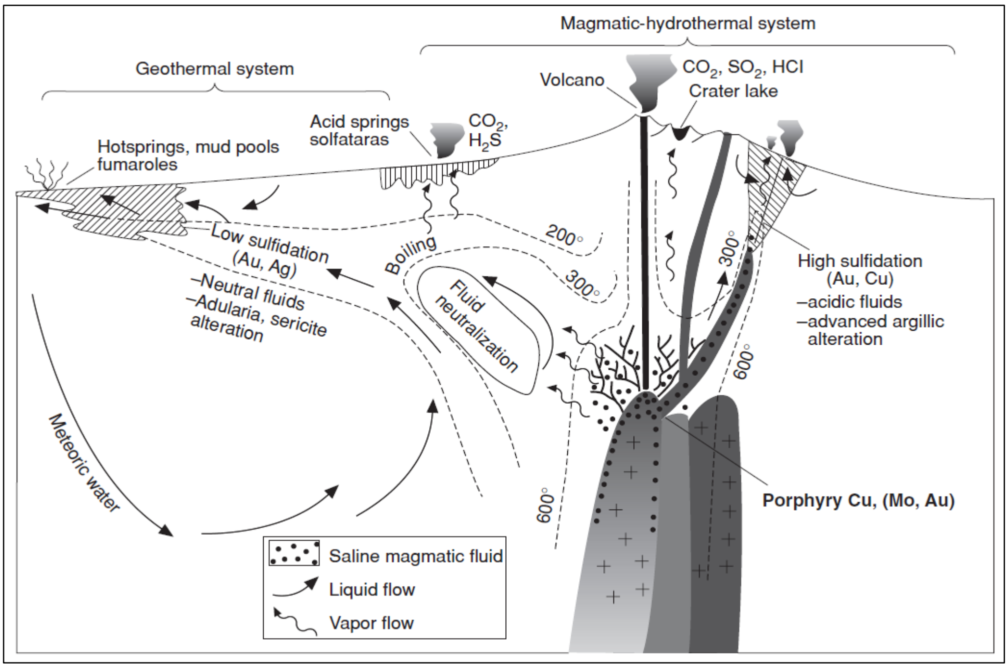


Figure 10: Formation of porphyry Cu (Mo, Au) and epithermal Au, Ag, Cu deposits Source: Hedenquist et al., 2000

Sulphides of Fe, Cu and Mo are the most common ore components, but minerals of Pb, Zn, Au, W, Bi and Sn can also occur. 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). Deposits are typically semicircular to elliptical in plan view. The median size of the longest axis of alteration surrounding a porphyry copper deposit is 4–5 km. In cross section, ore-grade material in a deposit typically has the shape of an inverted cone (Berger et al. 2008). Ore bodies are embedded in an alteration halo comprising fractured and brecciated rocks. Upward the mineralisation may show a transition to a high sulphidation epithermal system *(Figure 10).*

Porphyry systems are associated with the magmatism of intraoceanic island arcs or continental margin arcs, over subduction zones. 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 (Seedorff et al. 2005). The mineralisations and alterations form concentric zones along and around the main pathways of the fluids *(Figure 11).*

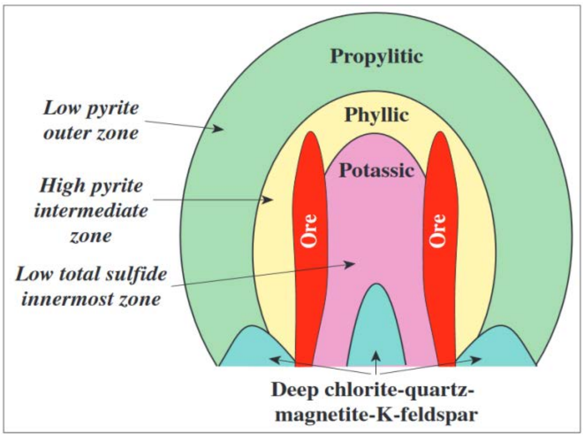


Figure 11: Cross-section of a porphyry copper deposit showing idealized alteration zoning. Source: Berger et al., 2008

Porphyry deposits are not generally the main target for the robominers technology because of the low ore grade and the disseminated distribution of the ore minerals. However, an exception could be made in those cases where there is substantial secondary enrichment of the ore, where a low-grade primary chalcopyrite ore is substantially enriched with secondary sulphides like chalcocite, bornite, and covellite.

4.2.4 Epithermal deposits

Epithermal deposits are frequently associated with porphyry systems. Epithermal deposits 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 300ºC 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 levelled with changing metal composition (Pirajno 2009).

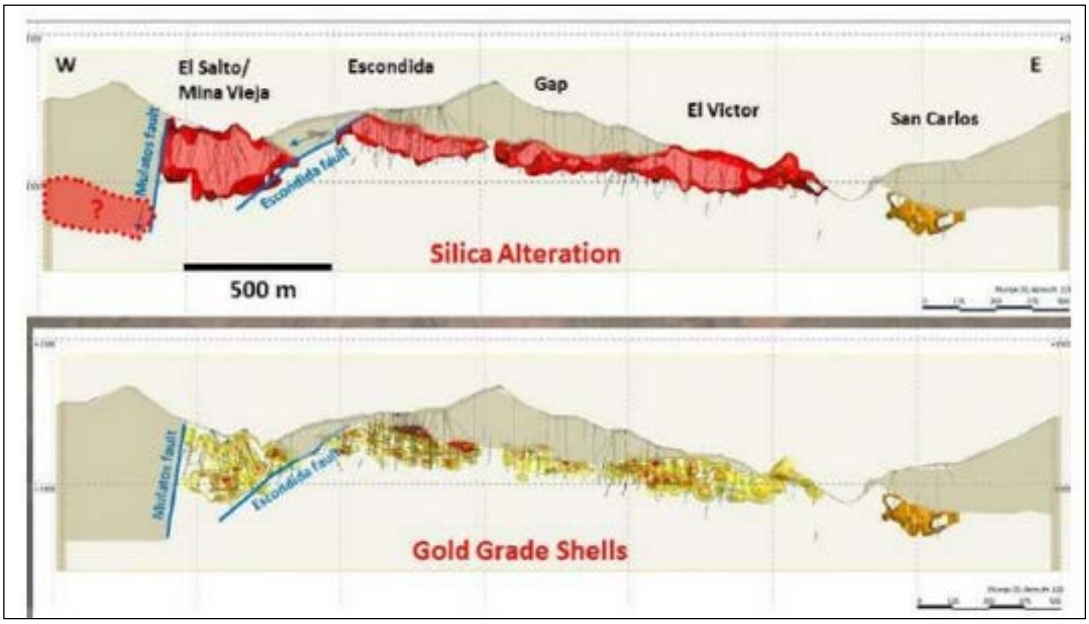


Figure 12: Section of the Greater Mulatos HS epithermal deposit, Mexico, showing silica alteration with gold mineralisation. Source: Aloro Mining report, http://www.thehedgelesshorseman.com/gold-silver-stocks/aloro-mining-next-steps/

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, Au-Ag tellurides and native gold are characteristic ore minerals. The ore bodies are typically brecciated pipes, lens-like or irregular forms *(Figure 12)*, the ore minerals are present in disseminated form. Typical metals are Cu, Au, Ag, As, (Pb, Ag, Sb, Te, Sn, Mo, Bi).

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 and calcite. The main ore minerals are native gold, sulfosalts, silver selenides and Au-Ag tellurides. Typical metals are Au, Ag, Zn, Pb, (Cu, Sb, As, Hg, Se). LS deposits show a great variety in textures but veins are the most frequent *(Figure 13)*. If the fluid ascent was near vertical, silica sinters cover the ore bodies.

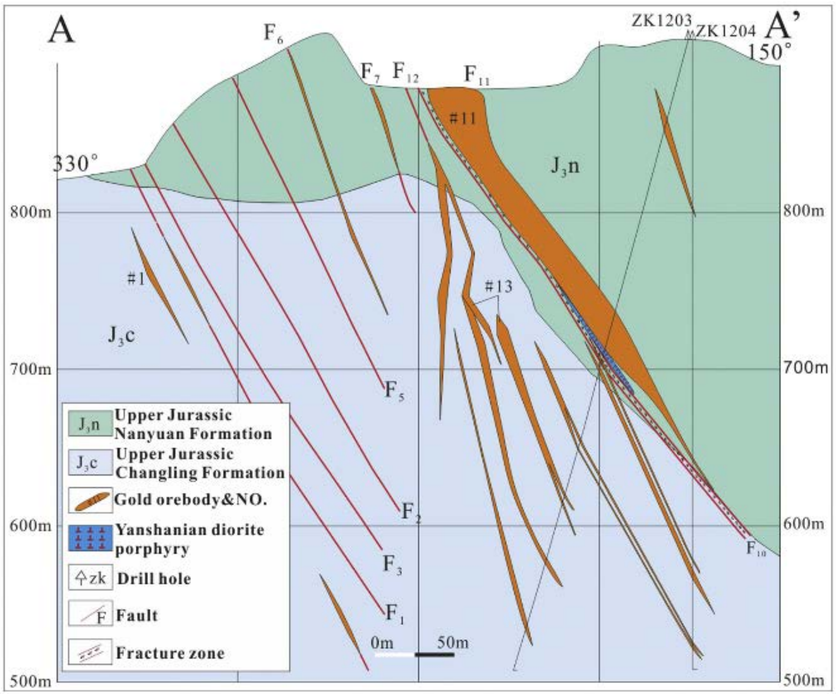


Figure 13: Cross-section of a part of the Qiucun epithermal LS gold deposit, China. The veins can reach 700 m in length and are 1 to 8 m wide with Au grade vary from 2 to 24 g/t. Source: Ni et al., 2018

Central and Eastern Europe, a relatively young pa

Epithermal deposits, especially the vein-like types are suitable for the extraction by robominers technology. They often have sharp contacts, which can provide a simple definition of the zone to be mined, though beyond the high-grade zones defined by these contacts there may be further metasomatic mineralisation, which the robot technology can extract if it can provide real-time reliable ore analysis.

4.2.5 Skarn deposits

Skarn systems develop when the magma gets contacted with carbonate country rocks, and the exsolved rt of the continent in terms of geological times, are the home of large-size Phaneorozoic 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.fluids react with the carbonate minerals forming calcium-silicates. 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).

When the metasomatism and replacement develop in the magmatic rocks, it is called endoskarn, while in the carbonate rock exoskarn will form. These deposits are extremely irregular in shape *(Figure 14);* tongues of ore may project along any available planar structure-bedding, joints, faults, etc.-and the distribution within the contact aureole is often apparently capricious. Structural changes may cause abrupt termination of the orebodies (Evans 1993).

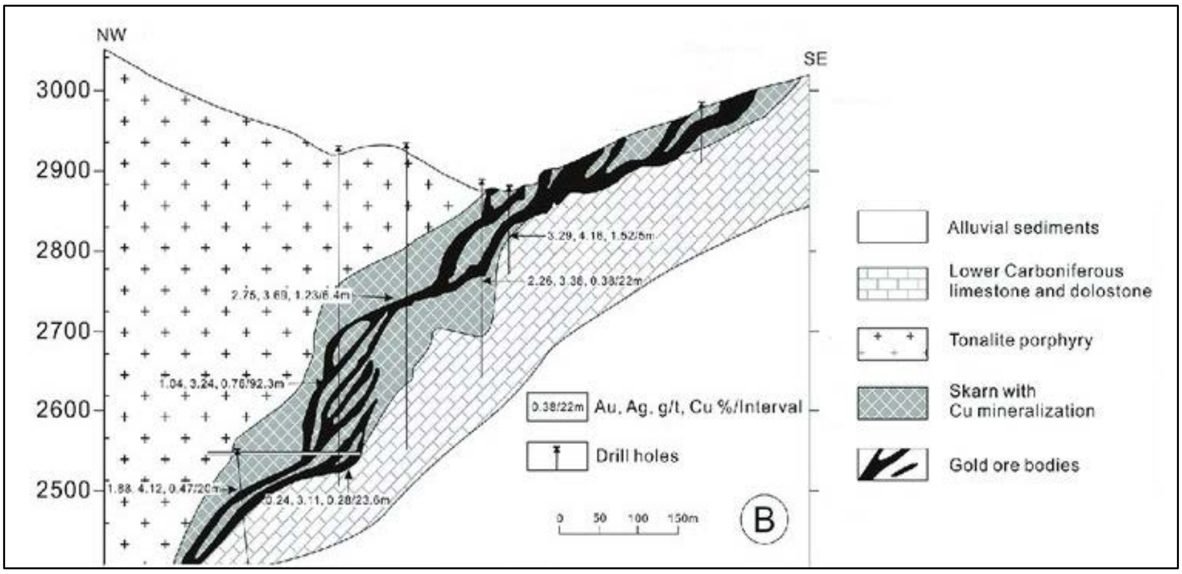


Figure 14: Cross-section of the Kuru-Tegerek skarn deposit, Kyrgyzstan. Source: Bo et al., 2019

Tectonic setting can be the same as in the case of porphyry systems (these two deposit types are frequently in direct contact), but in rifting environments skarns can also occur in contact with granitic plutons. Deep skarns (5-15 km) tend to be smaller than shallow ones, and these are mostly W skarns. Skarns have usually a zonation controlled by decreasing temperature and salinity of the fluids migrating outward. Ore is generally restricted to the exoskarn. Massive sulphide replacements and veins occur mostly in distal skarn zone (Meinert et al. 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).

Although skarn deposits form irregular ore bodies, they can be target of the robominers technology. Local enrichment of metals can be detectable and there are multiple fracture systems in the host rock which can benefit the extraction. Because the mineralogy and the metal associations can be complex, real-time decision-making in a robotic mining system will be heavily dependent upon reliable chemical and mineralogical analysis as well as economic evaluation of the blended ore feed. The discontinuity of many skarn deposits could be problematic for any ore-following algorithm and may require pilot drilling from the robot itself or advance drillholes from surface to identify and locate ore bodies.

4.2.6 Iron Oxide Copper-Gold (IOCG) deposits

IOCG deposits are magmatic-hydrothermal deposits that contain economic Cu and Au grades. The term IOCG was introduced following discovery of the giant Olympic Dam Cu-U-Au deposit in South Australia. These deposits are structurally controlled, and commonly contain significant volumes of volcanic breccia associated with sodic-calcic alteration. The brecciation and alteration zones have a large, regional-scale, relative to economic mineralisation. Abundant but low-grade Ti-Fe oxides and/or iron silicates are also characteristic. Fe-Cu sulphides are also present, and LREE and U are enriched. The pyrite is subordinate and there are no widespread quartz veins or silicification. The deposits show a clear temporal, but not close spatial relationship to major magmatic intrusions Their tectonic setting at formation was most likely anorogenic, with magmatism and associated hydrothermal activity driven by mantle underplating and/orplumes (Groves et al. 2010).

Magnetite-apatite bearing 'Kiruna-type' deposits can be considered as end-members of the IOCG deposits, although their origin is highly contentious. These P-rich iron-oxide deposits lack economic copper and most contain low amounts of gold. Many of the iron oxide (P) deposits display spatial, temporal, and probably genetic relationships to intermediate (commonly dioritic) composition intrusions. The iron oxide (P) deposits are not directly associated with major structures or structural zones as are the true IOCG deposits (Hitzman et al., 1992).

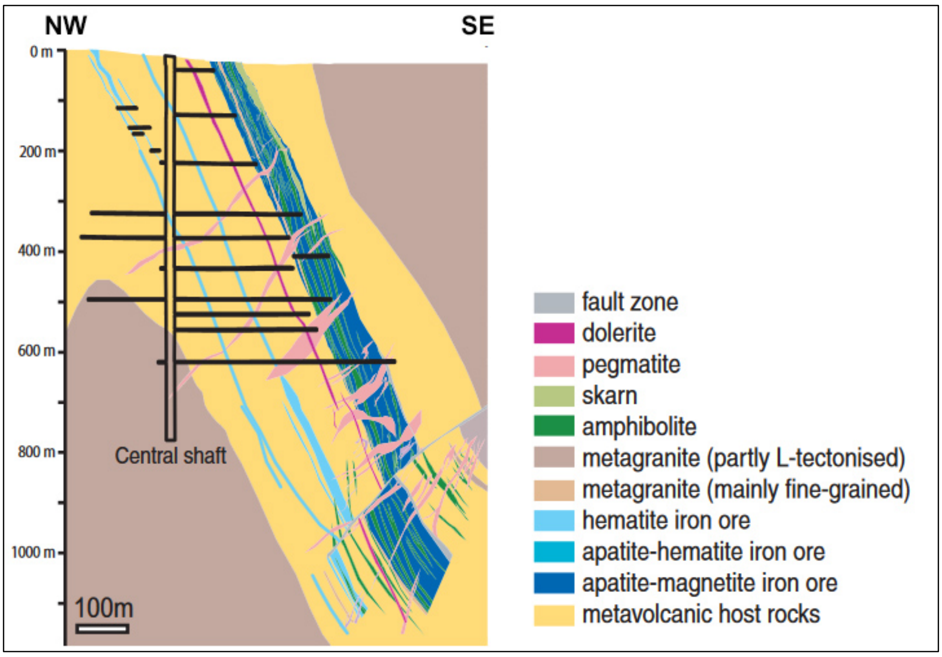


Figure 15: Cross-section of the Grängesberg Mining District in Central Sweden showing the different types of mineralisations. Source: Jonsson et al., 2013

The 'world-class' example of the IOCG deposits is Olimpic Dam, which is, at the same time the largest known single uranium deposit on Earth. In Europe, Sweden id the biggest iron producer, mostly from two principal regions, the Kiruna-Malmberget province in northern Sweden and the Bergslagen region in central Sweden *(Figure 15).* The apatite-iron-oxide ores of the Grängesberg Mining District represents the largest iron ore accumulation in the classic Bergslagen ore province (Jonsson et al, 2013).

As the ore is concentrated in sheeted, predictable structures, the Kiruna-type mineralisation is suitable for extraction with the robominers technology. The sheets are well defined and easy to follow, but their thickness means that the relatively small Robominers equipment will need to follow a carefully designed multi-layer extraction plan. Because of the high grade of these deposits, there may be insufficient mineral processing waste to provide backfill for necessary support of openings, and mine plans would need to provide for support pillars.

4.3 Hydrothermal deposits

As opposed to the previous section, 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.

Hydrothermal mineralisation processes mean precipitation and crystallisation from the vapour or from the liquid phase of aqueous solutions, typically during loss of heat and pressure. Beyond the p-T changes, the process is controlled by further physicochemical factors like fugacity of various components or redox potential and acidity. The changes of these imply reactions with the permeated rocks or mixing of solutions of different composition.

Water is an omnipresent compound in the Earths lithosphere, often bound in minerals like amphiboles. This water can be released by metamorphic or other alteration processes, or by partial melting of water containing minerals (see 4.2 Magmatic-hydrothermal deposits). Enhanced heat flow reaching rock bodies with water saturated pore space adds connate formation water and groundwater of meteoric origin (with the possibility of recharge) to the hydrothermal system, multiplying the volume of the involved fluids.

Mobilisation of the chemical elements requires destabilization or disintegration of the carrier mineral phases and appropriate chemical form to be transported by the fluid. Elements commonly concentrated in minerals, which are relatively stable in most possible lithospheric conditions (e.g. Zr and Hf in zircon). Elements, which are not compatible in most hydrothermal fluids (e.g. high field strength elements, HFSE) can be regarded as immobile in the hydrothermal processes. However, there are special environments of hydrothermal activity where HFSE or other "immobiles" can also be mobilised. Most widely distributed and abundant hydrothermal enrichments contain alkali and alkaline earth metals, iron, base metals (copper, lead, zinc) and precious metals (gold, silver) in the form of sulphide, sulphate, carbonate, oxide and hydroxide minerals.

Transport of heat, water and further compounds of the rocks are interrelated. Heat and fluid influx, or evolution of a fluid phase can trigger the heat flow: local increase of the fluid pressure will decrease the effective stress in the rock, which can cause the opening of cracks and voids, forming pathways to fluid flow. As heat conductivity of the rocks is low, the heat flow will be largely enhanced by convection. Moreover, the same effect (decrease of the effective stress in presence of fluids) can also lead to partial melting of the rock, so magma flow may be added to the process. On the other hand, emplacement of an intrusive magmatic body in an originally cooler country rock may generate further hydrothermal fluids by heating the connate water or groundwater of the contacted formation. Magmatism and hydrothermal activity are often conjugated with each other, so deposits of these two origins are also related.

Mineralisation may happen by crystal growth in pores or by substitution of pre-existing minerals of the host rock. It requires physicochemical changes, which are significant enough to reach supersaturation in the solution for the components of a given mineral. As velocity of such changes is relatively low, it happens mostly on sites where the flow meets an obstacle, or where the parameters change abruptly. This is a cyclic process usually, even if the fluid recharge is continuous. Porosity may be temporally variable; if precipitation fills the voids, it decreases the permeability, so the flow will slow down or stop. That will cause fluid pressure to increase, inducing opening of new fractures, which again may channel the flow until precipitation seals the pathway. In tectonically active zones, slip events along fault or shear zones may control the process by reopening the fractures.

As each component of a solution may need different parameters to reach inequilibrium, several parageneses may develop from the same hydrothermal system. The site of mineralisation for certain mineral assemblages is variable, both in time and space. One mineralisation event on a given site produces almost pure mineral phases or assemblages of few phases, so differentiation and local enrichment of chemical elements (even for those, which are not abundant elsewhere) can be very efficient, but the volume is restricted, and the next event on the same site may not evolve the same mineral composition. A typical feature of a hydrothermal mineralisation is the zoning, but the zones may overlap and overprint each other. Similarly, a void filled by subsequent events may have a banded structure of alternating mineralogical-geochemical composition.

In the Earth's crust, the common pathways for fluid flow are joints. Geometrically related (parallel, radial etc.) joints form joint sets. Those joints which were active during a deformation phase form a joint system. Joints reflecting the fracturing in an earlier deformation event remain preformed surfaces of weakness within the rock, so may be reopened in subsequent phases, e.g. by increasing fluid pressure.
Within the hydrothermal group, there is a large variety of deposit types. In this section, beside the genetic factors, the commodities, the morphology and geometry, and the environment of the given deposit are considered.

The list of the hydrothermal deposit types here is not complete, only the most important ones that are represented in Europe are described:

- Vein association deposits
- Volcanogenic massive sulphide (VMS) deposits
- Sedimentary exhalative (SEDEX) deposits
- Mississippi Valley type (MVT) deposits
- Stratiform sediment hosted copper (SSC) deposits
- Orogenic gold deposits
- Carlin-type ore deposits
- Sandstone hosted uranium-vanadium deposits

4.3.1 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. For example, pegmatitic or greisen deposits can also form veins. However, as many hydrothermal deposits occur in veins, in this study we describe hydrothermal vein associations as a separate group and characterise veins in details because they are important target mineralisations for the robominers technology.

If deformation relates to hydrothermal activity, mineralisation can form veins by filling the opened joints. The orientation of the veins is controlled by the stress field and the mechanical anisotropy of the host rock. As due to the gravitational load, the highest principal stress is vertical in most situations, joints and consequently veins also tend to be vertical or subvertical. In several cases, however, the veins follow contacts of different rock types (e.g. bedding, fault zones) or planes of mechanical anisotropy (cleavage).

Veins do not penetrate the rock bodies evenly. Joint sets may often be localised to smaller regions of the rock body, e.g. to the hinge of a fold, to a competent layer within a ductilely deformed succession, or to a shear zone. Pattern of the veins is controlled by the style of the deformation.
Individual veins may be thin (<cm in diameter) tabular objects of few square metres area, which are not economic. In the vein mineralisations of economic interest, the sizes are larger (lodes), or the spacing of the small veins is dense enough, and the vein material exceeds the host rock in volume at least in

meter-scale zones or penetrating even larger host rock bodies (stringer lodes). Such zones may form along several structures, but most appropriate precursor for forming a lode is a fault zone *(Figure 16).*

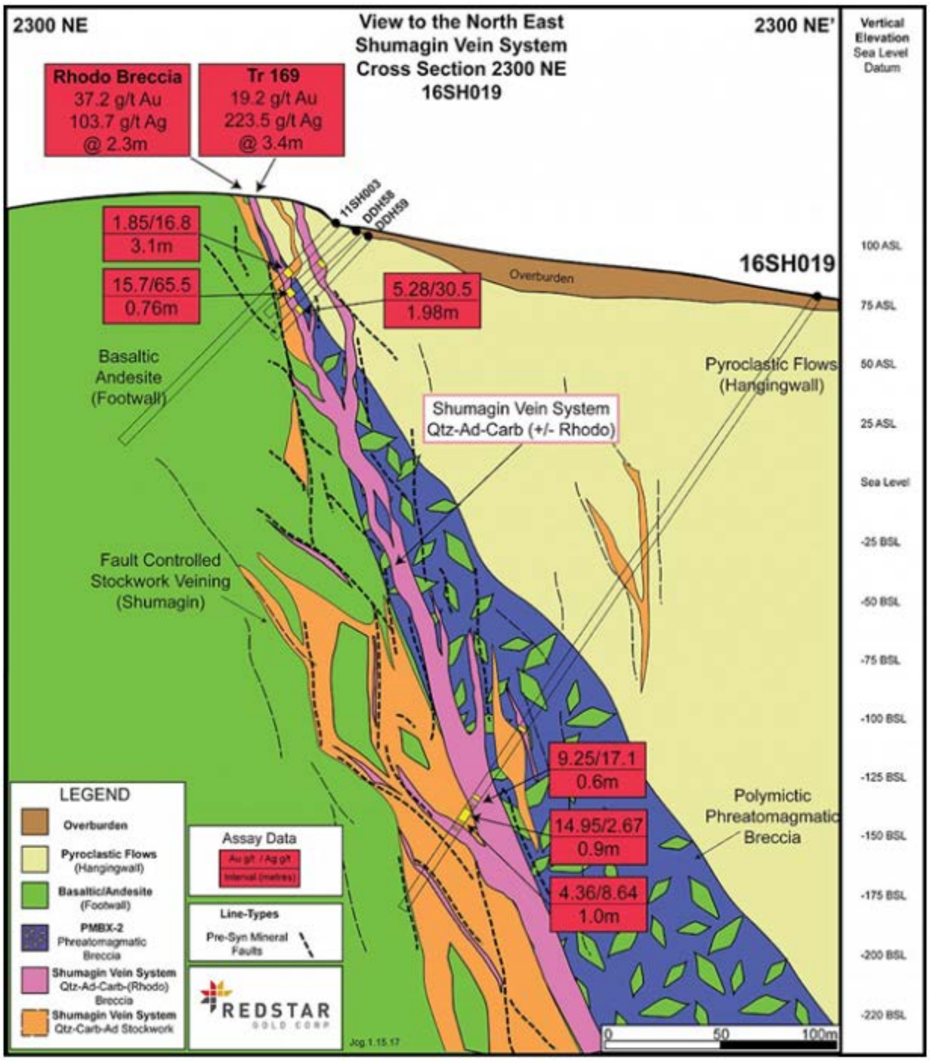


Figure 16: Conceptual cross-section (to scale) of a gold-silver vein system in Orange Mountain, Unga Island, Alaska. The lode consists of several branching and crosscutting veins of variable orientation along a fault zone of constant dip, formed at the contact of different rock types. Veins are surrounded by voluminous breccia and mineralised rocks (stockwork) in the damage zone of the fault. Assayed productive intervals are including these rock types.
Source: https://www.redstargold.com/site/assets/files/3093/cross-section-2300ne.615x0-is.png

Although faults are usually depicted as lines on maps and profiles, these are 3D structures. Complex fault systems of regional importance may reach the thickness and depth of several kilometres, and the length can reach tens and hundreds of kilometres. Lodes hosted by such structures may also reach the same magnitude; the largest known example is the 190 km long gold bearing Mother Lode in California. However, hydrothermal fluid flow is concentrated in most cases in relatively narrow, subvertical channels (vents or chimneys) along the faults. Economically useful mineralisation also tends to concentrate around such upstream channels.

The slip on a fault plane proceeds in seismic steps which involves opening of several fractures. The wall rock of a fault is strongly fractured relatively to the country rock, having a porosity increasing toward the core. Thickness of this damage zone is usually in a larger order of magnitude than that of the core. High velocity fluid influx in the suddenly opened space may add hydraulic fracturing and brecciation to the common grinding effect. Faults crosscutting impermeable formations or connecting permeable ones with each other channel the fluid flow and concentrate the mineralisation.

Mineralisation shows a vertical zoning both in mineralogical and geochemical components. These zones are classified traditionally as hypothermal, mesothermal and epithermal mineralisation (Lindgren 1933). As the names suggest, composition is controlled mostly by temperature (listed in decreasing order), while structures depend on stresses, so the two aspects are not necessarily interdependent, but they tend to coincide. Therefore, veins and lodes abundant in the shallow (>1 km) levels of the lithosphere host epithermal assemblages mostly, while on deeper levels stockwork, disseminated and replacement ores dominate.

Within a lode, there is also a vertical zoning of the gangue and ore minerals. It means also a change in mechanical and hydrological properties, as a vuggy quartz-dominated gangue typical on the top level may be harder and more porous than the country rock, while carbonate or argillic gangue of a deeper zone may be the opposite, softer and impermeable.

Around the lodes, at least in the damage zone of the precursor fault, there is always a zone where the host rock is altered by metasomatism. Such aureoles, even if they do not contain economically useful mineral and metal enrichments, may be used for tracing the expected deposits: tendency of change of certain geochemical features within the aureole can be used as a vector pointing toward the orebody. But it is also a common feature that ore minerals do not necessarily occupy the veins, associated with the gangue; highest concentrations of the useful metals might be found in the matrix of the breccia or in the altered country rocks.

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 the ore complexes in South-West England and Erzgebirge in the Czech Republic and Germany.

The vertical extent of many vein systems can be very large, to several kilometres depth, with zonation (as described above) which may be complex due to different phases of mineral emplacement. This is one environment in which robominers technology may provide a unique solution to mineral extraction, as parts of the veins will be ultra-deep and the cost of pumping could mean that workings will be permanently flooded. Extraction of minerals from narrow vein deposits is also suited to robominers technology. Conventional mining of such deposits is expensive whether using manual/semi-manual methods (slow, labour intensive) or using normal mining equipment (with extraction of large proportion of waste from footwall and hangingwall). The small size of robominers equipment would allow rapid extraction with minimum of human labour and minimum production of waste rock.

4.3.2 Volcanogenic massive sulphide (VMS) deposits

Volcanogenic massive sulphide (VMS) deposits are associated with rifting and ocean floor spreading zones, an extensional tectonic regime where hot mantle material is moving upward, and the lithosphere is thinned extremely. This type is not classified as magmatic-hydrothermal because hydrothermal fluids are believed to be brines of seawater origin. 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. The fluids originate from seawater, which circulates through the basaltic crust and dissolves metals. 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).

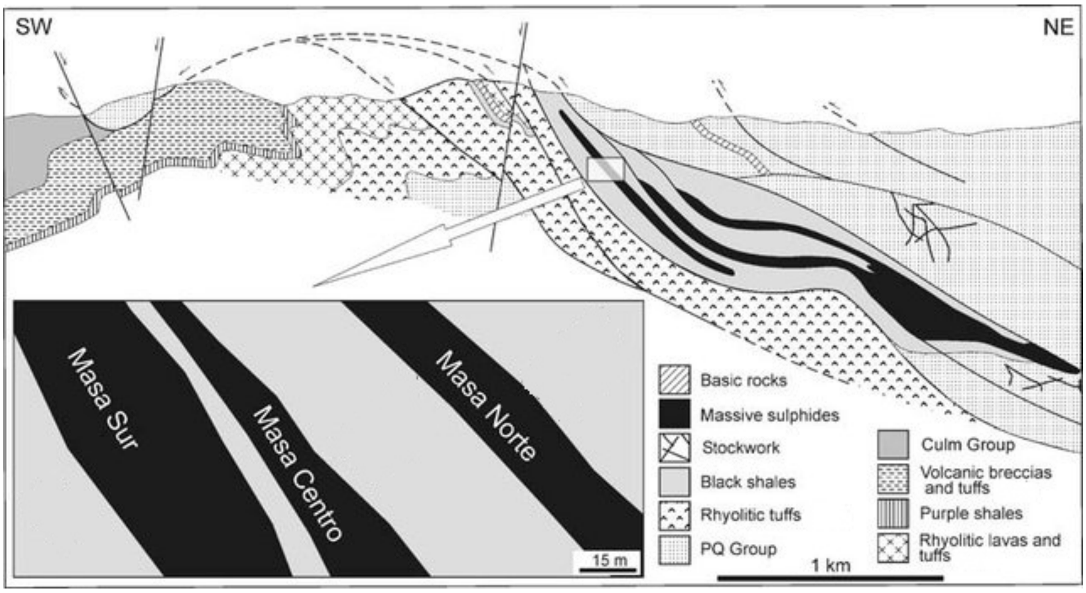


Figure 17: Cross-section showing the lithostratigraphical and structural interpretation of the Sotiel-Coronada area in the Iberian Pyrite Belt. Source: Gonzáles et al., 2006

VMS deposits form massive or layered, laminated ore lenses *(Figure 17)*. World-class base metal deposits were formed in this way e. g. in the Iberian Pyrite Belt, the largest ones at Rio Tinto and Neves Corvo. In the area of the Fennoscandian Shield, there are also important European VMS deposits. Outokumpu, Finland, is a high grade Cu deposit containing minor Co, Ni and Zn. 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).

This deposit type is suitable for the application of the robominers technology because of the well identifiable metal concentrations. The geometry of such deposits can be complex, and this would dictate the use of long pilot drillholes to establish a suitable mining layout and strategy, though with largely continuous deposits a simple ore-following algorithm may be sufficient.

4.3.3 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. The mineralisation in both cases has limited lateral extents around hydrothermal vents, but reaches considerable vertical thickness (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 and most important district of this type is the Irish metallogenic province where a large number of base metal deposits are hosted in sedimentary rocks *(Figure 18)*. 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).

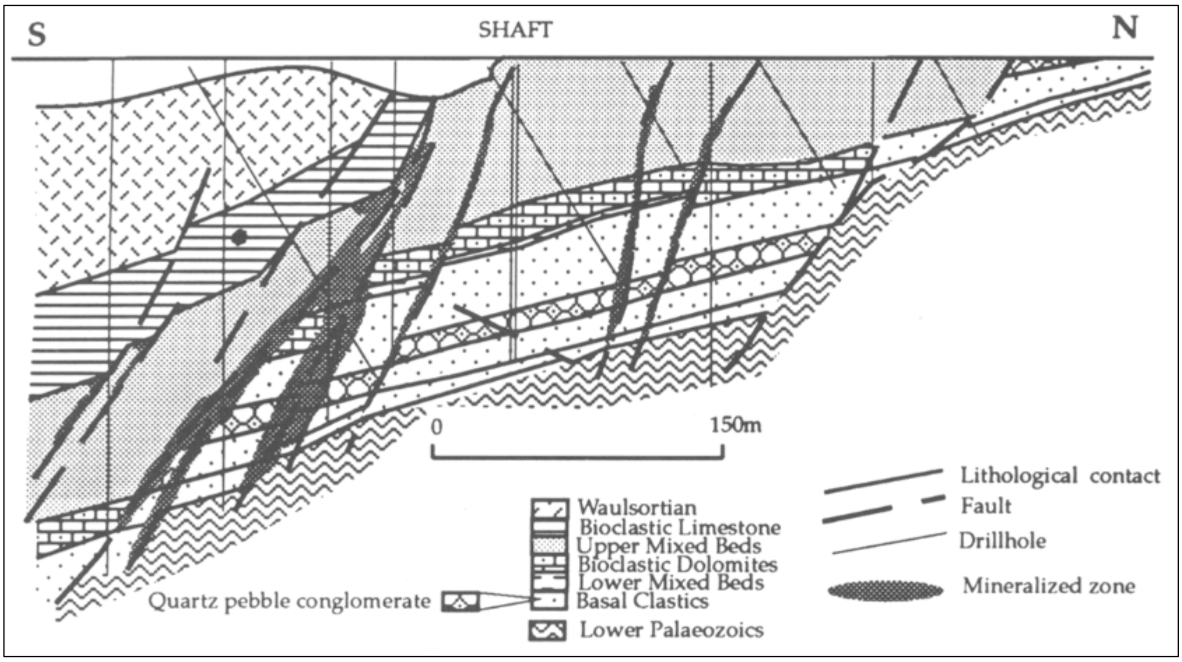


Figure 18: Cross-section of the Keel deposit, Ireland, showing the intimate relationship between faulting and mineralisation. Source: Johnston et al., 1996

In the Harz Mountains, Germany, the Devonian Rammelsberg and Meggen are similar deposits, with Cu, Ag, Pb, Zn and Ba as main metals. These two exhausted occurrences represent one of the oldest mining districts of Central Europe.

Similarly to the VMS type, Sedex deposits can also be considered as targets of exploitation with the robominers technology.

4.3.4 Mississippi Valley type (MVT) deposits

MVT ore deposits are Pb-Zn mineralisations hosted mainly by dolostone and limestone in platform carbonate sequences. Silver is commonly also an important commodity, but Cu content is generally low (Leach et al 2010). MVT deposits 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 deposits are generally strata-bound (limited to one rock formation) but also can be structure controlled *(Figure 19).* In the case of the strata-bound deposits, a geochemical barrier, i.e. highly reactive media in the flow pathway induces a zone of mineralisation. Extents and geometry are determined by the shape and pores of the rock body containing the reactive component. A typical situation is when an acidic hydrothermal fluid permeates a carbonate (limestone or dolomite) rock body. An impermeable cap rock and the presence of organic matter or pyrite (sulphur) in the carbonate may also be essential in promoting the precipitation of metals. Porosity of the carbonates may be enhanced by precursor karstification.

MVT and SEDEX deposits are similar in many aspects; both are sediment-hosted Pb-Zn mineralisations. The main difference is that SEDEX ores are synsedimentary (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 in Poland developed in a flat-lying, platform Triassic carbonate limestone and dolomite (De Vos et al. 2005).

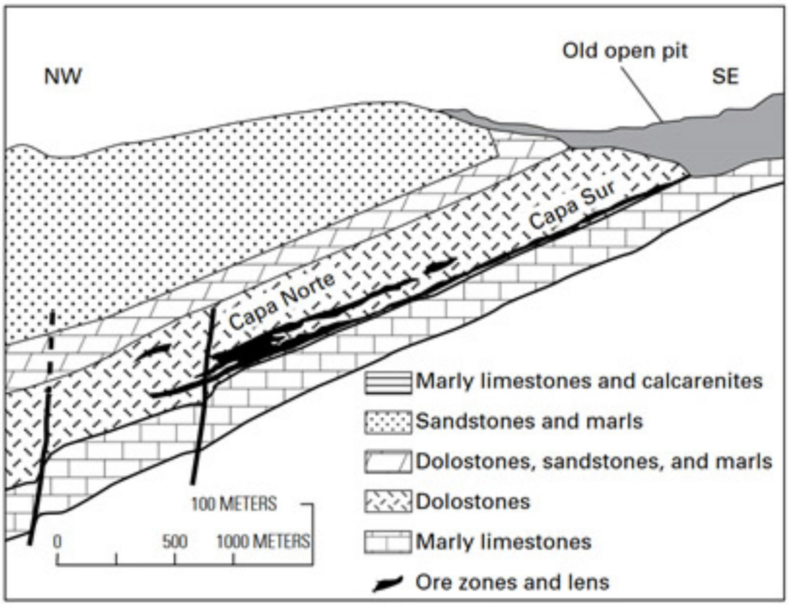


Figure 19: Strata-bound and structure controlled MVT deposit. Cross-section through the central part of the Reocin deposit, Spain. Source: Leach et al., 2010

This deposit type is suitable for the application of the robominers technology because of the well identifiable, predictable geometry. The carbonate host rock, with its relatively low hardness, is also a benefiting factor in the exploitation. In some cases, MVT deposits occur within paleo-karst structures as cavern-floor or cavern-lining mineralisation. This is common, for example, in the Carboniferous limestones of central and northern England. In these cases, deposits have highly irregular geometry, but the use of an ore-following algorithm combined with pilot-hole drilling makes robominers technology highly suitable for exploitation of such deposits. One potential hazard is unpredictable roof collapse if there are pre-existing openings in the karst structure. The risk can be minimised if appropriate instrumentation (something as simple as video cameras) is included in the robot.

4.3.5 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.

Stratiform ores are deposited in sedimentary successions (typically interbedded in black shale of restricted basin facies). Metals and sulphur as the mineral components may originate also from these sediments. 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).

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 *(Figure 20).* Basically it is an ore of Cu, Pb and Zn but also contains the enrichment of a series of other metals like V, Mo, U, Ag, As, Sb, Hg, Bi, Se, Cd, Tl, Au, Re and PGE. The thickness varies only between 0.3-4 m, but it is a continuous bed extending throughout North Central Europe, from Poland to England, also in the basin of the North Sea. Active mines reach a depth of 1200 m. Although the bed itself may be continuous, the metal content can change significantly because of subsequent remobilisation. The horizon has been mined in several sites where it is in near-surface position, mainly in the southern part of the distribution area, but a considerable part of it is covered by several kilometres thick younger sediments (Zientek et al. 2015).

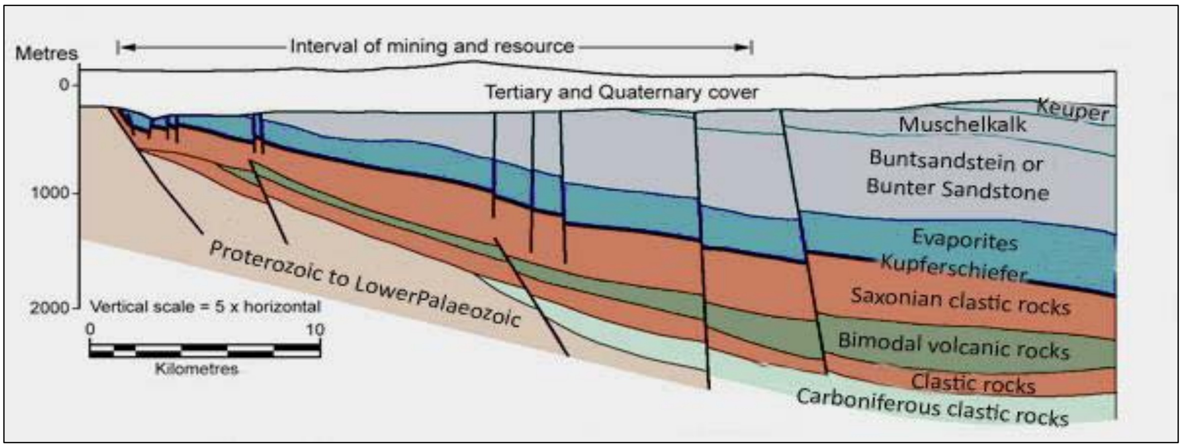


Figure 20: Geological section across the Fore-Sudetic copper district, Poland. Source: http://www.portergeo.com.au/database/mineinfo.asp?mineid=mn401

Because of its geometry, accessibility and predictability, the Kupferschiefer is an excellent target of robominers. Optimal extraction of ore would require a combination of analytical instrumentation for the multiple target metals together with real-time ore-following algorithms. In thicker parts of the Kupferschiefer, it would probably be necessary to use a multi-layer mining strategy. Because of the great depth of the horizon in many places, pumping would be prohibitively expensive and the robominers system would need to operate in some hundreds of metres depth of water.

4.3.6 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 H2O-CO2 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. The main ore control is structural, along major shear zones or overthrusts. The ore appears in banded vein- or pod-like structures. The late timing of the formation of orogenic gold deposits within the structural evolution of the host orogen implies that any earlier structures may be mineralised. This means that the current structural geometry of the gold deposits is equivalent to that at the time of their formation if there has been no significant post-gold orogenic overprint. Anticlinal or antiformal fold hinges provide one of the more robust parameters for location of orogenic gold deposits *(Figure 21).* World-class orogenic gold deposits are commonly located in the deformed volcano-sedimentary sequences or along the zones of assembly of micro-blocks on a regional scale (Groves et al. 2018).

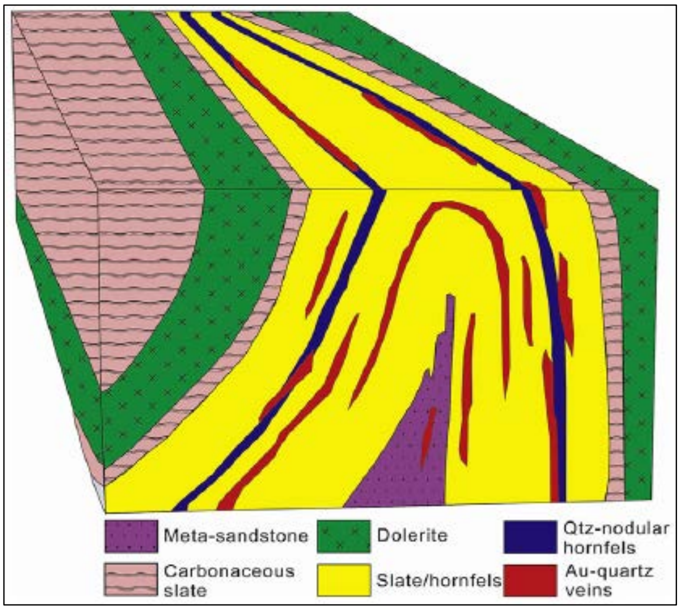


Figure 21: Simplified cross section of Paleoproterozoic Cosmo Howley deposit, Pine Creek Gold Field, N.T., Australia. Source: Groves et al., 2018

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.

The high concentration of the gold in many of the veins makes this deposit type suitable for extraction by the robominers technology, though the geometry of individual veins can be complex, controlled by structure of the host rock. Ore-following algorithms using real-time gold grade determination are necessary to make robominers as effective as possible. Because of the difficulty of accurate gold assaying in situ, it may be necessary to use proxies such as arsenic to follow the highest grade ore shoots.

4.3.7 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). In the last decades, promising exploration successes have led to discoveries and intensification of explorations of this ore type.

Fluids source in the 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 *(Figure 22).* The precipitation mechanism may be related to neutralisation 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.

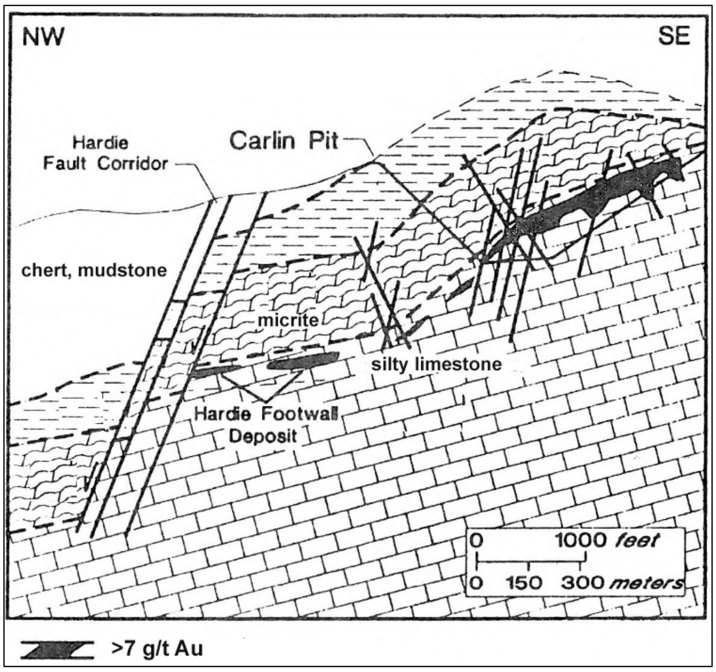


Figure 22: Cross-section of the Carlin and Hardie Footwall deposits. Source: Hofstra, 1999

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

Because of the relative low concentration of gold and the disseminated character of the ore, Carlin-type deposits are not the main target of the robominers technology.

4.3.8 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 U6+ forms stable complexes at near-neutral pH, and significant large tonnage low grade deposits can form. It may occur that coarser-grained classic sediment host the mineralisation *(Figure 23).*

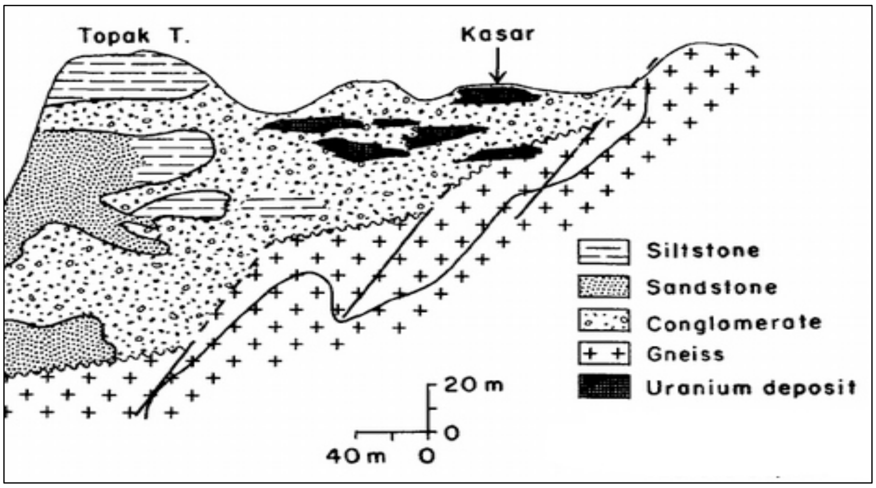


Figure 23: Cross-section of the uranium deposits hosted by fine-grained conglomerate, Menderes Massif, Turkey. Source: IAEA, 1985

Sandstone uranium deposits are widespread throughout Europe, dominantly of the Permian sandstones (Novoveska Huta, Slovakia; Allier, France; Zirovski 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).

As uranium is concentrated in lenses and the host rock is clastic sediment, this deposit type is suitable for extraction by the robominers technology.

4.4 Sedimentary deposits

In the former sections, there were deposit types where the ore mineralisation occurred in sedimentary rocks, but the mineralising fluid originated from magmatic or hydrothermal fluids. Sedimentary ore deposits are formed by specific sedimentation processes (Bradley et al. 2013):

- physical weathering, transportation and separation by weight, size or hardness,
- chemical weathering and selective mobilisation,
- diagenetic processes, transport by groundwater, re-precipitation,
- precipitation from the seawater, brine pools or salt lake water under specific conditions.

Most of the sedimentary deposits are series of beds or lenses, which may be alternating with intercalated barren sediments. From our point of view, those sedimentary deposits are important, which do not lie on the current surface, but are part of deeply buried, diagenetised or metamorphic successions. Most of these were tectonically reworked, which decreased the continuity of the beds, e.g. competent ore beds embedded in an incompetent matrix will be dissected by boudinage during ductile deformation with layer-parallel extension. Such subsequent processes may obscure the origin and transform the geometry of the deposits significantly. Nevertheless, bedding parallel trends are retained even when bedding is tilted, folded or dissected by faults.

Within the sedimentary group, the following deposit types are described:

- Bauxite deposits
- Placer deposits
- Banded Iron Formations (BIF)
- Ironstone deposits
- Bedded manganese deposits

4.4.1 Bauxite deposits

These deposits form at continental surface or near-surface environments. Laterites are the products of intense weathering of outcropping basaltic rocks in tropical regions, under humid and warm climate as residual sediments. They are economically important as they represent the main environment within which aluminium ores (bauxite) occur. They can also contain significant concentrations of Ni, Mn, Au, Cu and PGE. Weathered zone extends to 30-60 m to the depth. An important variation of this mineralisation is when the weathering products are redeposited on underlying karstified limestone (karst bauxite), filling well shaped dolines with a thickness of several ten metres (Wilson 1983) *(Figure 24)*. Enrichment of REE is also characteristic for many bauxite deposits.

In Europe, karst bauxite is produced in the Mediterranian region. Greece is the major producer, but there are also key occurrences in Turkey, Bosnia-Herzegovina, Montenegro and Kosovo. Former significant mining activities were in France, Hungary and Italy.

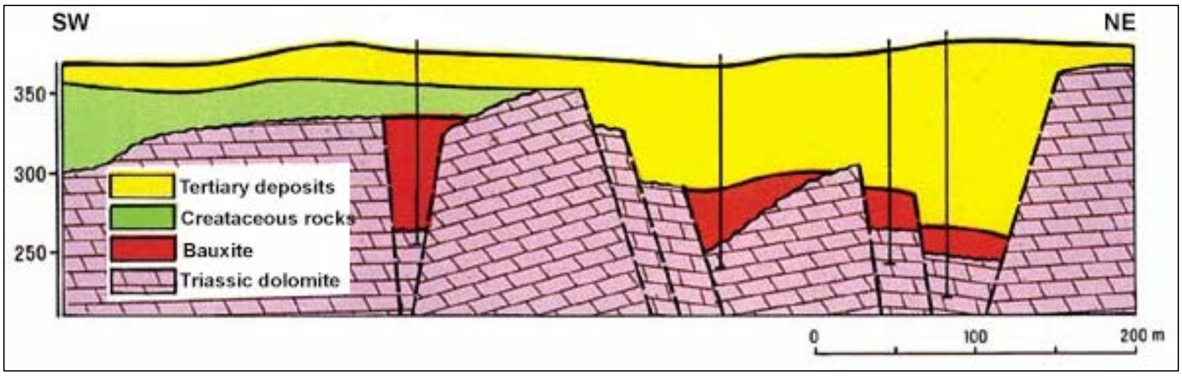


Figure 24: Cross-section of the karst bauxite deposit in Iharkút, Hungary. Source: https://www.arcanum.hu/hu/online-kiadvanyok/pannon-pannon-enciklopedia-1/magyarorszag-foldje-1D58/asvanyok-kozetek-banyakincsek-229B/bauxit-mindszenty-andrea-245F/a-karpat-pannon- terseg- bauxitelofordulasai-2470/

These deposits may be very suitable for robominers extraction. They often consist of relatively small ore bodies which are individually uneconomic to exploit by conventional mining methods. A simple short-lived robotic extraction cycle, replacing extracted mineral by backfill which may be waste from the mine itself or may be waste from other nearby mines or quarries, would have minimal environmental impact in either short term or long term.

4.4.2 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).

Marine placers are band shaped sediment accumulations. Mineralised beds are usually thinner than 1 m, but kilometres-range horizontal extents can make them economic. Continental placers may be easily accessible resources, but these are temporary formations with even more limited horizontal extents, rarely preserved as paleoplacers in older successions. The final depositional environment is in most cases the seashore in and around the estuary or delta of a river. There are examples, however, where large alluvial fans host extended coarse grained beds enriched in heavy minerals, similar in geometry to the stratiform ores. The largest gold resource of the world, the alluvial conglomerate beds of the Witwatersrand Basin is debated in origin, whether it is a placer, a hydrothermal mineralisation or the combination of the two kinds (Tucker et al. 2016).

In Europe, there are no significant placer deposits. In general, placer deposits tend not to be suitable for robominers technology because although they may be easy to mine (unconsolidated sediments) the mineral grades are generally very low. In Arctic regions (Russia, Alaska, Canada) there are gold-bearing placer deposits which are extracted from shallow underground mines in permafrost ground, and which may be suitable for robominers, but the very low temperatures are a potential problem (for slurry transport, for example).

4.4.3 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 altering 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 worldwide, there are no significant occurrences in western or southern Europe. In the Fennoscandian Shield, there are BIF deposits at Kostomuksha in Russia. However, as with most BIF deposits these are relatively low grade and can be exploited economically only by large scale open pit mining. They are not suitable for robominers.

4.4.4 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 either was 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 and formerly in south-eastern England represent ironstones. They are typically low-grade mineralisation and are of little interest for robominers exploitation.

4.4.5 Bedded manganese deposits

Bedded manganese deposits are close relatives to BIF iron ores, but with manganese dominance. Normally these are Mn-oxides (pirolusite) or Mn-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 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). Because of the large size and relatively low grade of these deposits, they are most efficiently exploited in large open pit mines and are of little interest for robominers.

5 GEOMETRY OF ORE DEPOSITS AND ITS IMPLICATIONS FOR THE ROBOMINERS TECHNOLOGY

For mine planning, the geometry of ore deposits is a basic determining factor. The genesis of the deposit should also be considered but similar mining methods can be used for deposits of different minerals that originated in different environments. For example, longwall mining is conventionally used for many coal deposits - but it can also be used for stratiform evaporites such as the potash deposits around Soligorsk, Belarus.

In nature, ore deposits are rarely present as simple geometrical bodies. Rather they tend to form complex and irregular 3D structures in the rock mass. Their shape is driven by the sedimentological, tectonic, stratigraphic, mineralogical and other factors during formation of ore deposits, as well as by the post-mineralisation tectonic regime, weathering and geochemically-driven changes in post-mineralisation/sedimentation phases. All of these factors influence the geometrical occurrence of ore minerals in the host rocks.

In general, we can observe three basic (overall, large-scale) geometric shapes of ore bodies:

- One-dimensional (linear) ore bodies: e.g. pipes, diatremes, volcanic vents *(Figure 25)*;
- Two-dimensional (planar) ore bodies: e.g. stratiform deposits, veins, ore layers from magmatic differentiation (e.g. PGM and chromite), mineralisation along fault planes;
- Three-dimensional ore bodies: e.g. porphyry copper deposits, diffusion-driven and other metasomatic ore bodies.

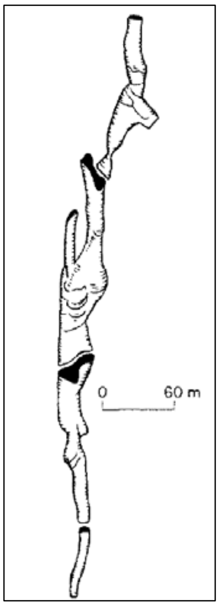


Figure 25: 'One-dimensional' (tubular) ore body. Vulcan tin pipe, Herberton, Queensland. Source: Evans 1993

The overall dimensionality of an ore body does not necessarily control the mining strategy or mine layout. For example, deposits hosted in volcanic vents (such as diamond-bearing kimberlites) tend to be hundreds of metres across and for our purposes should be considered as three-dimensional deposits. Thus, attribution of dimensionality (1D, 2D or 3D) depends on the scale of the deposit relative to the scale of mine development.

Most deposits of economic significance will look three-dimensional on a scale of centimetres, but on larger scales, their true dimensionality becomes apparent - thus an epithermal gold vein will be seen to be two-dimensional on a scale of metres, or a nickel laterite deposit will be seen to be two-dimensional on a scale of tens of metres.

For the robominers technology, the important scale that we must consider is about a metre, as this is the size of the robots being developed. Below this scale (millimetres to centimetres) there could well be highly irregular distribution of ore minerals within a host matrix, but this is of little concern to the mining operation itself, as the robot will not have the capability to selectively mine at such small scales. It is of course important when considering the ore cutting and mineral processing technologies to be used, so detailed rock-face analysis can be important for this purpose - but this only affects processes that take place after rock fragmentation and extraction.

The important parameters here are the form (size, shape) and distribution of ore mineral grains, and it is possible to extract such information in the form of automatically estimated statistics including grain size distributions, fractal dimensionality (an indication of the complexity of mixing of the different mineralogical components of the rock fabric), etc. For all practical mine planning purposes, deposit geometry needs to be considered as either two-dimensional or three-dimensional.

5.1 Two-dimensional deposits

These deposits may have different thicknesses and any orientation. Although locally planar, they may be curved (folded) and/or discontinuous (faulted).

If substantially thicker than the size of the robot miner, such a deposit should be considered three-dimensional for the purposes of mine layout design and mine scheduling strategy.

Such deposits are highly relevant for the robominers technology. The robot miner will be much smaller than conventional mining machines, so it will often be able to precisely extract only rich vein material, without extracting too much surrounding waste rock. As a rule of thumb we might say, that the best vein thickness could be in the range 10-100 cm for common ore minerals. It is important to note that the thickness of vein-type ore bodies is much less than their horizontal or vertical extent. Veins can go down to the depth of several kilometres and their length can be even tens of kilometres *(Figure 26).*

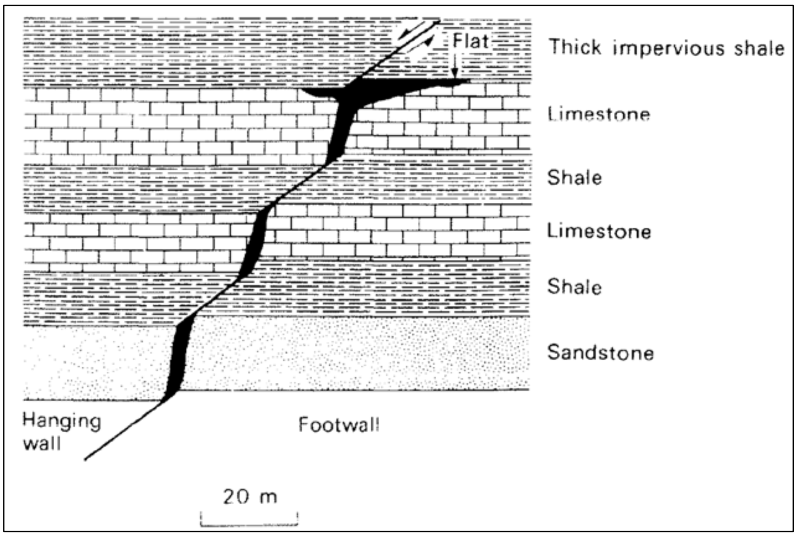


Figure 26: Vertical section of a vein exhibiting pinch-and-swell structure. Note that the horizontal and vertical extent of the vein can be kilometres. Source: Evans, 1993

Mining strategies can use either pre-defined mine layouts if the deposit is known to be regular with well-defined footwall and hanging wall - as in many coal seams or magmatic deposits such as PGM and chromite reefs - or for less regular deposits may be dynamic, defined by a combination of an ore-following algorithm and geomechanical considerations such as roof stability.

If there are multiple parallel, branching, or intersecting two dimensional ore bodies, it is likely that the structure will be less well defined in advance, and a modified ore-following algorithm may be the only option. Advance drilling and estimation of ore grade in different layers or veins would be required to allow selection of the optimum mining direction at intersections or where ore bodies are branched. This is especially important in cases where a decision to mine a particular layer precludes later extraction along other layers. A well known example of this is extraction of a thick coal seam which lies below thinner seams. If the thick seam is extracted first, it may prevent exploitation of overlying seams because rock fracturing during subsidence makes this too hazardous.

If intersecting veins are particularly closely spaced, such as in a stockwork deposit *(Figure 27)*, the deposit as a whole may best be considered as three-dimensional, and no attempt need be made to mine the veins separately.

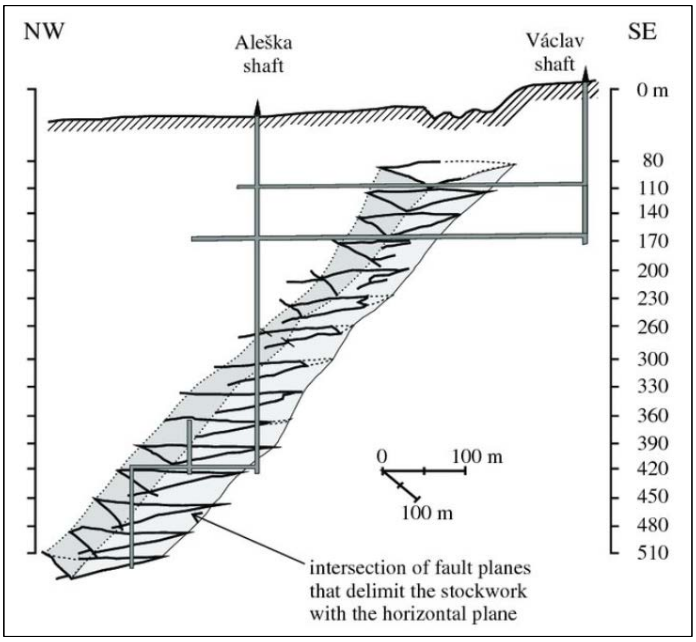


Figure 27: Cross section of the Roudny ore deposit, Bohemian Massif. The stockwork delimits four main, interpenetrating faults, which form an irregular prism. Source: Zacharias et al. 2009

5.2 Three-dimensional deposits

Three-dimensional deposits are deposits which are generally either too thick for extraction in a two-dimensional mine layout, or have a complex three-dimensional geometry such as in a system of branching or intersecting veins *(Figure 27)*. There are, however, deposits that are truly three-dimensional. Typical of these are

- Metasomatic deposits of many types: skarns *(Figure 28)*, limestone-replacement deposits (in MVT mineralisation), and pipe or irregular deposits formed by diffusion of hydrothermal mineralising fluids around feeder channels;
- Brecciated zones, where ore minerals are found whether in the breccia matrix, or as clasts, and similar.

Many such deposits would be amenable to extraction by robominers technology, given suitable mine planning and production scheduling algorithms. Critical factors would be the stability of openings. A variety of mining strategies are possible:

A multi-level pseudo-two-dimensional approach could be used. The robot miner could simply follow the deposit in one plane in many directions and stop when average grade gets too low. When finished at one level, the miner descends/ascends to another level and repeat the operation. If backfilling, starting at the bottom, provided the backfill is sufficiently compacted or cemented, this would yield 100% extraction of the deposit with no cutting of waste. Special attention must be placed to assure stability and to prevent collapse especially taking into account the physical properties of backfill material, so the mining strategy must be precisely defined in advance by mining engineers, and programmed in the miner.

Many three-dimensional deposits such as porphyry copper/molybdenum/gold are conventionally mined using block caving or related methods. Such a mining method could be achieved by robominers, but it must be recognised that in conventional mining there is often a need for human intervention to clear blockages in ore-passes that can be a result of infrequent fragmentation - i.e. large boulders wedged in the ore-pass that require additional breaking. This can be very dangerous, and a robotic approach to such mining could save miners' lives.

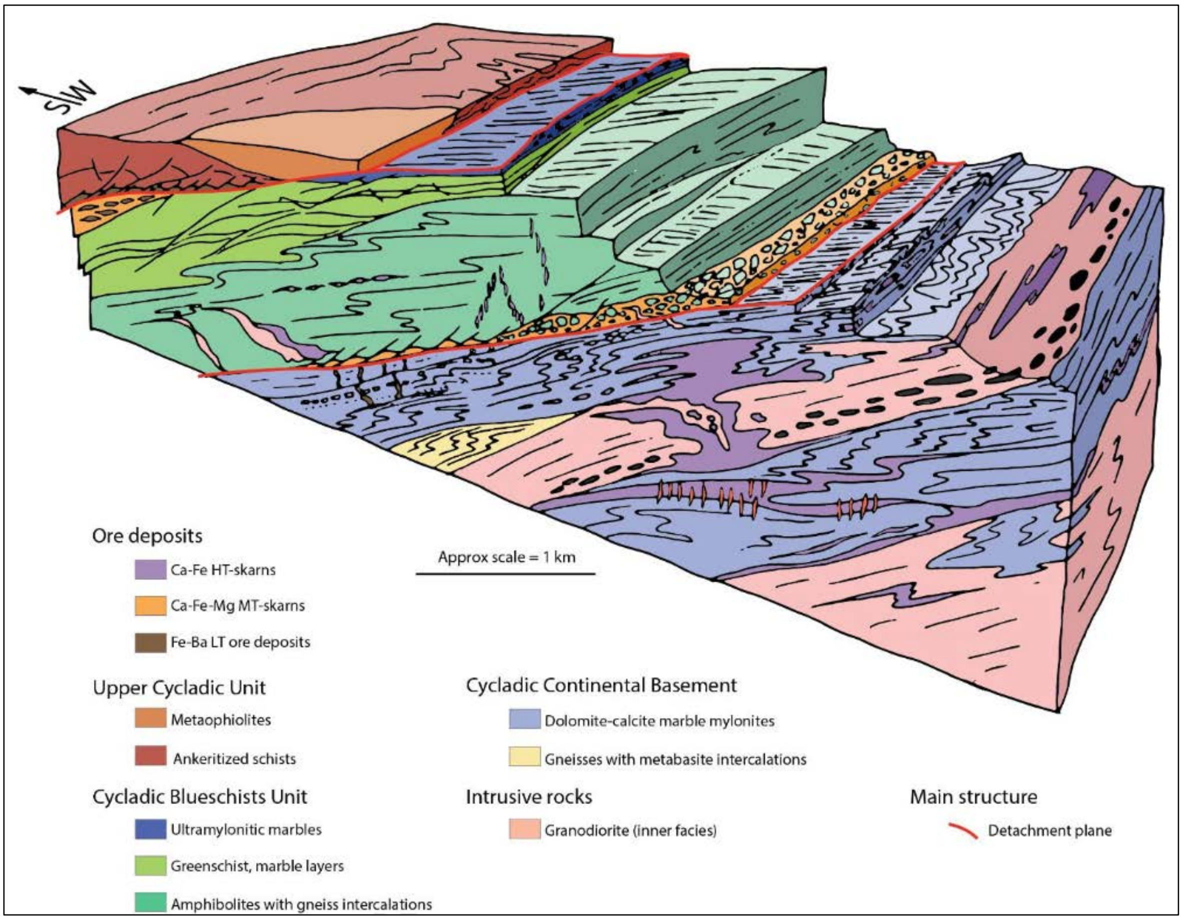


Figure 28: Three-dimensional diagram of the SW part of Serifos, Greece, summarising the main lithostratigraphic units, both detachments and the structural position of different skarns. Source: https://hal-insu.archives-ouvertes.fr/insu-01412398/document

For highly irregular three-dimensional deposits (containing high-grade pockets and knots of mineralisation), the robotic miners using an ore-following algorithm can in principle generate a highly complex network of tunnels and other workings similar to those seen in many ancient hand-excavated mines. This would allow selective mining on the scale of the robot miner itself (i.e. down to one-metre thickness). It would require the robot miner to have the capability to operate in any orientation - horizontal, upwards, or downwards - with delivery of mined material as a slurry. Limitations would necessarily be imposed by the power of pumps used and the strength of material of the pipes used for slurry transport.

Many three-dimensional deposits are simply very large by comparison with any mining equipment. These types of deposits include massive deposits, as in many magmatic deposits (i.e. some chromites), greisen, porphyry, epithermal deposits, laterites, bauxite, sandstone hosted uranium deposits, VMS, banded iron formation deposits and similar. The common factor is that the ore body is far larger in all directions than the robotic miner itself and that no direction is dominant. These are generally rich or easy-to-mine deposits, so they are commonly targeted by conventional mining techniques, often in large open-pit operations. However, if ultra-deep, flooded, geomechanically unstable, or in any other way unsuitable for conventional mining, these can be interesting targets for the robominers technology.

5.3 Mineral processing considerations

Selective mining - in the sense of separating ore from waste - can be achieved by the robot miner at a scale smaller than the width of the miner itself.

Fragmentation and processing are dependent upon smaller-scale rock structure - the rock fabric. This includes the size and shape distributions of mineral grains, and their spatial relationships (random, brecciated, schistose, etc. rock fabrics) as well as the overall rock hardness and toughness.

Spatial relationships can be summarised by a geometric parameter: the "fractal dimension", and this could be used as an indicator for such selective mining. For example, it is possible that there is a contrast between the rock fabric of the host rock (e.g. a schist) and the ore vein (crystalline quartz). The estimated fractal dimension can be used to select best extraction strategies for a specific ore type.

The most common and easiest way to determine fractal dimension D is the box-counting method (*Equation 1;* Peitgen et al. 2004), and this method can be applied also to non-self-similar objects, for example, ore bodies.

The box-counting method is based on dividing the plane, for example, an open tunnel face or side wall, where ore body is found, into equal squares. The number of squares is s^2, meaning that each side of a square plane is divided into s equal segments. Then the algorithm counts how many squares are occupied with the mineralisation, and this value is the value $a(s)$. During the calculation of the fractal dimension, this procedure must be repeated at least twice, with two different values of s. Then we can determine fractal dimension D using Equation 1.

$$D = \frac{\log a(s2) - \log a(s1)}{\log 1/s2 - \log 1/s1} \text{ (Equation 1)}$$

To obtain a better result, the procedure should be repeated several times with different values of s. The dimension in this case is represented by the coefficient of best-fitting line of points ($1/s_n$, $a(s_n)$) plotted on a log-log scatterplot. Because an estimated diameter of the robotic miner (as of March 2020) is 1 m, we can also estimate the desirable values of s, which could range between 2 to 64 (0.5 m to 1.56 cm size of a square). However, s values could be also larger, if the resolution of the sensors allows that.

Fractal dimension is a quantitative parameter that may be determined objectively by image analysis and can be used in defining local mining strategies.

5.4 Ranking of ore deposit types by the applicability of the robominers technology

During the second project consortium meeting on 14 January in Tallinn, a technical working group session was held on the geological and mining aspects of the robominers technology. The aim of the session was to select the appropriate deposit types and mining scenarios.

A five-level scale was set up and the deposit types described in *Chapter 4* were ranked by the workshop participants from 1 (not applicable) to 5 (fully applicable) according to most relevant aspects. Results of the ranking process are shown in *Table 1*. During the procedure, the following four factors were considered:

– *Geometry.* This could be chosen as primary classification aspect, with the basic types of stratiform, stratabound, vein-type, disseminated and massive ore bodies.
– *Rock mechanics – stability*. The importance of stability is that the robot shouldn't be lost. Stabilisation of the small holes of robominers technology can be secured in several ways, so

maybe this is not crucial when ranking the deposits. Vertical shafts are easier to stabilise and to transport the exploited material.

- *Rock mechanics – extractability.* For locomotion of the robot, hard rocks are preferred. Depth may mean problems because of temperature limits of hydraulic technology. Hardness should be considered also relatively to the country rock. Soft ores may be preferred; however, a vein filling can be hard (quartz) and soft (clay) in a given location of the same system.
- *Economy and criticality*. As most economic deposits are those, which can be exploited without robominers technology, the project has to concentrate on such resources where exploitation may be expensive but the specific value of the ore is high, or it includes critical elements. Raw materials which are available in large quantities on the market are not favourable because small scale mining won't make any difference in the supply. Gold, PGE, tin or rare elements in high concentration may be appropriate targets; iron, base metals, industrial minerals are not.

Table 1: Ranking of ore deposit types using a five-scale pointing system and considering four determining factors (outcomes from the working group session at the Tallinn consortium meeting)

Ore type	Geometry	Rock mechanics - stability	Rock mechanics - extractability	Economics	Ranking ∑
SSC (Kupferschiefer-type)	5	4	4	4	17
Hydrothermal veins	4	3	4	4	15
Pegmatite	4	4	3	4	15
VMS	4	3	4	4	15
Carbonite alkali REE	4	4	2	5	15
Cu-Ni-PGM sulphide	4	4	2	5	15
Epithermal (LS) vein type	4	3	4	4	15
Orogenic gold	4	3	3	5	15
Skarn	4	3	3	4	14
SEDEX	4	3	4	2	13
Layered chromite	4	4	2	2	12
Epithermal (HS)	3	2	3	4	12
IOCG	3	3	3	3	12
MVT	3	3	4	2	12
Bauxite deposit	4	2	4	2	12
Sedimentary manganese	4	2	4	2	12
Sandstone hosted uranium	2	3	3	3	11
Greisen	1	3	3	3	10
Podiform chromite	2	4	1	2	9
Carlin type ore	1	3	3	1	8
Porphyry copper	1	3	3	1	8

Deposit types with 15-17-point ranking are the best targets but deposits with lower point can also be selected depending on specific characteristics.

6 SUITABILITY OF ORE DEPOSITS FOR THE ROBOMINERS TECHNOLOGY

6.1 General conditions

In the starting model of robominers development, the equipment will be a bionically designed automatic machine, capable of moving, sensing ground conditions, carrying out on-line determination of ore chemistry, and extract ore from the stope walls. As a maximum size, a one tonne total weight machine is the recent (April 2020) concept of the key component of robominers technology.

A one tonne total weight machine is obviously uncompetitively light with regard to conventional underground mining equipment in conventional ore deposits. Nevertheless, technological changes in high-tech industries require new ore types, in many cases in low quantity but high specific value. These are, in many cases, by-products of conventional extraction operations, but exponentially increasing demand cannot be matched by exponentially increasing ore production for the main elements (e.g. indium production is linked predominantly to zinc ore mining). In addition, the smaller machine size allows for higher selectivity, i.e. the minimum required thickness of the ore body can be reduced to less than one meter.

In these cases, robominers can be a really efficient alternative. Other advantages of such a mine, like shorter lead time of development, smaller environmental footprint, working environment without working safety restrictions, etc., should also be well considered.

6.2 Factors of suitability

Apart from a real short- to mid-term market demand, three main factors govern the suitability of an ore enrichment for the robominers technology:

- specific metal value of the ore and other market conditions
- favourable geotechnical properties,
- commercial technologies to extract and refine metals from ores.

6.2.1 Specific metal value of the ore and other market conditions

Specific metal value data have been collected from the available internet sources to gather deeper knowledge of this parameter of the market. This is illustrated in *Figure 29*. It should be noted, that purely the metal price itself is not decisive, but at least many of the low-value commodity types can be excluded from the further investigations.

The elemental composition may also be ambiguous to judge the value of the ore (like the difference in specific value of diamond versus graphite, both of them elemental carbon minerals). Naturally, the price estimates are sometimes far from the actual contract prices. Therefore, in *Figure 29*, a colour coding is applied to show which price group the actual element belongs to. The price groups are per magnitudes i.e. 1-10, 10-100, 100-1000 and >1000 USD/kg metal. The price estimates are based on a detailed internet research which was carried out in July 2019. In the majority of cases, the price information comes from the Chinese market, where we took the lowest published value at the moment of the search. The data show that apart from the six PGE elements (Pt, Pd, Rh, Ir, Os, Ru), a few other chemical elements, Au, Re, Sc, Rb, Ge, Lu) also reach the >1000 USD/kg metal value.

The table in *Figure 29* does not give any information about the market size and offer/demand conditions of the elements. In this regard, it may be a guide to use the EU criticality list of elements in *Figure 30* (European Commission 2017).

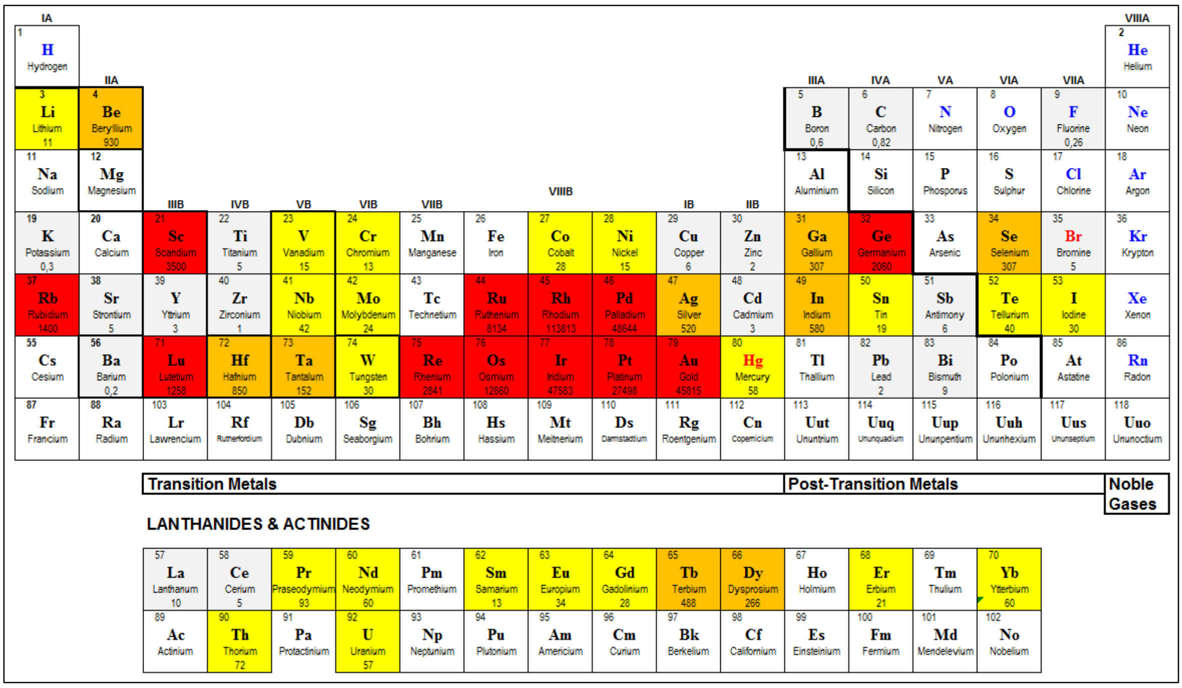


Figure 29: The approximate metal value of different elements, as appear in market quotes. Price groups are per magnitudes: grey: 1-10, yellow: 10-100, orange: 100-1000, red: >1000 USD/kg metal (data are based on internet research in July 2019)

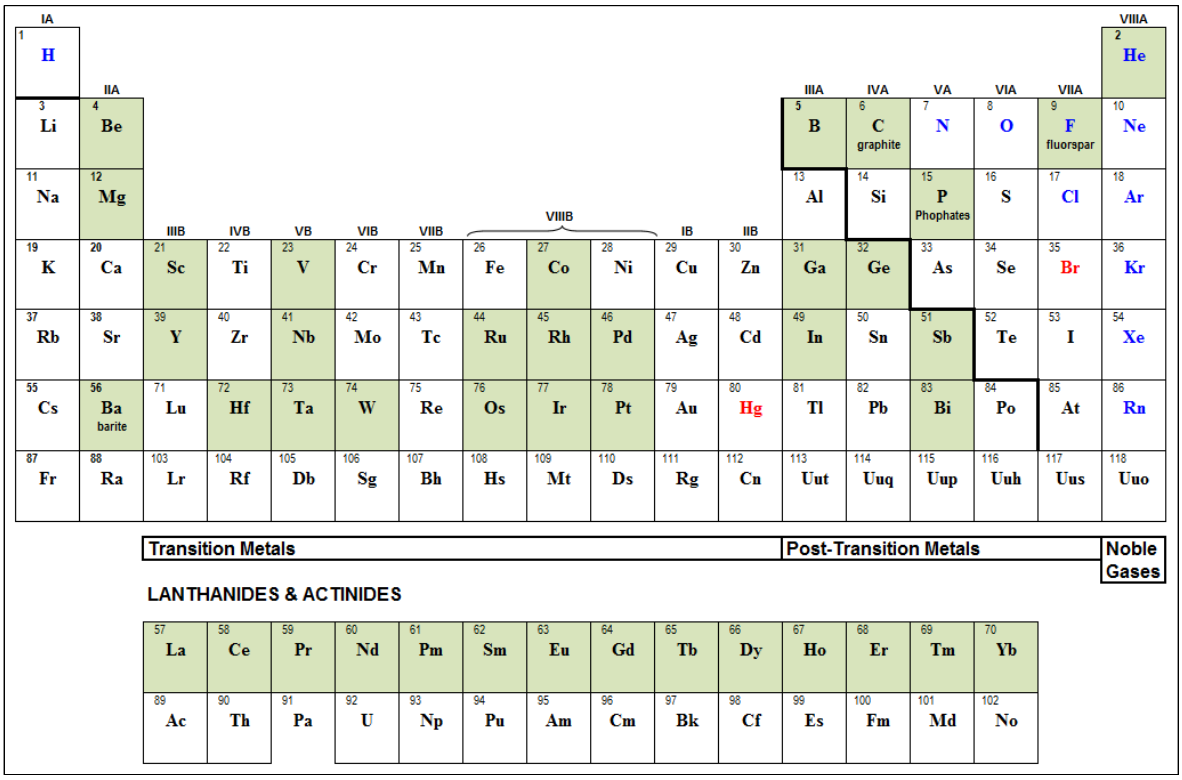


Figure 30: Critical elements of the EU list highlighted in green in the periodic table

As it is shown, the criticality condition does not overlap with the highest metal value range groups, some low specific value minerals (like barite, fluorspar, etc. are also on the criticality list. This list forecasts increasing demand and decreasing or high-risk supply in mid-term to long-term from these commodities in the EU countries, thus representing a strong and possibly stable internal market drive for these minerals.

On either list a great number of elements are now produced from minerals in which they are not the main components (like Ge from coal, Ga from bauxite), therefore in a more advanced stage of the project the analysis should be extended onto the host minerals/rocks containing the target metal.

6.2.2 Geotechnical and operational conditions

When planning the production development, geotechnical and operational conditions of access and production seriously modify the in-situ value of a mineral enrichment. In the case of robominer, these conditions differ from the traditional mining, and have a strong impact on the economic viability of the operation. The conditions are as follows:

- depth,
- ore deposit geology, setting,
- rock hardness, homogeneity,
- roof and floor conditions,
- ambient temperature and ventilation,
- water hazard.

Depth
Although the manless operation eliminates a great number of challenges linked to depth, it is still affected heavily by the depth of operation, because it broadly defines the vertical size of the operation to be permanently and safely maintained and operated. Lithostatic pressure (appearing as rock pressure) increases roughly 0.2-0.25 bar/meter depth, hydrostatic pressure (appearing as groundwater pressure) increases 0.1 bar/meter depth. Geothermal gradient renders approx. 0.03 Cˇ/meter depth increase of virgin rock temperature in average European continental ground conditions. These parameters cannot be reduced by technology; instead, technology has to be adapted to such conditions. Mining in 5,000 m depth with this technology is not impossible, but all these modifying factors have to be accounted for.

Ore deposit geology, setting
Apart from mineralogical composition, other geological factors, i.e. geological and grade continuity, deposit shape and texture, deposit boundary, etc. play significant role in realising adequate grade control of the manless operation. In case of robominer, the favourable features are opposite to those of a large open pit:

- Mineralogical/chemical composition should be simple and well assessable by the on-line assaying units of the robominer (like radioactive spectrometry for U, Th);
- Deposit boundary should be sharp, preferably sub-horizontal, non-articulated and continuous, detectable by on-board geophysical or geological sensors of the robominer (like apparent resistivity change at limestone/shale interface);
- Texture of the deposit should be as massive for ore bearing minerals as possible – disseminated or fine-layered/banded textures may reduce the selectivity of extraction (like porphyry Cu ores).

Rock hardness and homogeneity
Rock hardness and homogeneity are as important as grade of the mineralisation. The traditional method of drilling-blasting-hauling-loading cycle is probably not adaptable for robominer, other extraction tools have to be developed. Since the machine can exert only moderate to low torque compared to traditional equipment, dissolution, melting, hydro-fracturing, etc. should be checked. Water-soluble minerals are better for robominer than water-insoluble minerals, which can be extracted only by different physical processes – grinding, percussion, fracturing, etc. Low hardness minerals/rocks (like talc, or potash) are preferred to higher strength minerals/rocks (like ultrabasic host rocks of PGE, Co, Ni, mineralisations).

It is difficult to assess the in-situ rock-hardness of an ore body. In this regard, RQD indexes of the drill cores, and Bond indexes of the ore material may give preliminary information. Rock inhomogeneity (hard portions in relatively soft surrounding rock, like chert nodules in limestone) within the deposit would cause unwanted machine breakdown, or serious decrease of productivity. Homogeneity is even more difficult to predict – in this sense, geological simulation modelling of the detailed exploration information would give assistance.

Roof and floor conditions
During the entire life of a production site (stope), the access roadways and the worksites have to be maintained safely open. Several rock types ensure such stability, but others not. The failure types can be continuous or accidental roof caving, floor upheaving, stope collapse etc. Although these failures do not bring personal injuries, like in the traditional mining operation, these can entirely stop a production site, leading to a provisional or permanent closure.

Unfortunately, hardness is in a number of cases inversely proportional to rock competence, i.e. the rock's resistance against rock stresses. In traditional mining, the support is provided either by sacrifying parts of the ore body as pillars (like in room-and-pillar mining) or inserting artificial support – rock bolts, props, torcrete. In the case of robominer, torcrete seems to be the most easily adaptable supporting method.

Ambient temperature and ventilation
In traditional mining, where presence of human workforce is inevitable, ambient temperature is a serious limiting factor. For example, according to Hungarian mine safety regulations, no continuous work is allowed over 30C° ambient temperature. Mines with high ambient temperature (due to, for example, depth) require cooling. In traditional mining, this cooling is supplied primarily by the ventilation system. For proper ventilation, a mine has to be at least two entrances – for the ventilation system an intake and an exhaust one.

Robominer operation will by no means so sensitive to temperature and ventilation, since robots may be designed for higher operation temperature. Their electric drive will produce no exhaust gases to ventilate and dilute, but excess heat should also be taken away. However, due to continuously developing friction heat, permanent cooling of the cutting heads will be necessary in all case on the face as well. Using closed water circulation for cooling of machines working on the faces, auxiliary heat pumps may take away the produced heat, for further utilisation.

Water hazard
Robominer, by its original concept, does not require dewatered mine environment to operate. However, working in dewatered underground openings is much easier than underwater. Probably, the robominer unit can be prepared for either working condition, but not for both at the same time, i.e. groundwater conditions have to be explored in detail before developments. Due to the small cross sections of the stopes and access drifts, even small inrush rates (in the range of litre/min) can be paralytic to the whole operation, as well as inrush pressure shall be high. As alternative measure, continuous dewatering through surrounding dewatering holes can be a solution.

6.2.3 Commercial technologies to extract and refine metals from ores

Run-off-mine ores of robominer operation can be similar but not identical to traditional mining. Traditional ore processing starts with primary (coarse) crushing (for example starting 500 mm diameter to 100 mm). The robominer extraction will produce high-grade ore materials, which require no further coarse crushing. This technology will transport extracted mine products possibly in wet form out from the stopes, i.e. settling, dewatering, thickening is required before further processing may start.

The small volume of operation probably does not allow investing in an on-site processing plant. The highly selective robominer technology will produce pre-concentrates, which can be transported to remote processing plants at allowable cost. A nearby active processing facility is therefore a strong point in determining the economic feasibility of a geologically favourable site. Further processing probably follows well established technological traditional flow-sheet.

6.3 Robominers technology requirements for different deposit types: summary

In order to be appropriate for the range of deposit types considered (magmatic, hydrothermal, sedimentary) the following capabilities are required, though not necessarily all in the same robot module of a multi-module system:

- advance directional drilling (centimetres to metres ahead) to identify continuation direction of an ore body
- choice of mining production units (cutting/explosive/cavitation/LIBS/water-jet/percussion drilling/...); different units will be required for ore and host rocks of different hardness/toughness.
- real-time chemical analysis for multiple target elements
- real-time mineralogical analysis
- mine layout design and extraction scheduling algorithms (in surface control room)
- ore-following software algorithms (in surface control room; perhaps later in autonomous mining system)
- underwater operational capability (for deep vein and stratiform deposits)
- video camera(s) for hazard detection
- first-stage mineral processing to separate a concentrate feed from waste rock (likely simple gravity separation for heavy metals)
- capability to move vertically as well as horizontally

Additionally, not explicitly identified above,

- slurry pumping system to transport mineral concentrates to surface and waste rock slurry to a backfill location
- rock-bolting or other tunnel stabilisation system in a separate module to maintain structural integrity of the mine
- battery recharge system, either fixed (at shaft bottom) or mobile (e.g. induction charging of mining modules at the mining face)
- location method in the absence of GPS
- communication system between robots and surface control room

7 POSSIBLE GEOLOGICAL AND MINING SCENARIOS FOR THE ROBOMINERS TECHNOLOGY

The favourable scenarios for the robominer technology would have parameters, which are different from that of the traditional mining. Benefits in one side are offset by disadvantages on the other.

In Europe, there are significant obstacles against mining as it is thought to cause intolerable surface disturbance. Since robominers mining will be highly selective, and in most cases waste can be recycled as backfill, such operation is a viable alternative for these areas, if other technical and economic parameters met. Since the operation is through drill holes, no voluminous headgears of hoists, loading-unloading facilities will be necessary. Complemented with backfilling, no significant surface waste disposal is needed, further reducing the land demand and the need for further long-term maintenance and monitoring of these installations. In addition, rehabilitation of such minimal-art surface setup will be considerably cheaper than at the traditional mining systems.

Another aspect is safety. Hazardous tasks in the mining industry are quite common. That is why robots work recently in harsh underground environments where access for human beings for work is not possible or dangerous. This was the main drive of developing underground mine automation. The best world example is the Kiruna iron ore mine in northern Sweden. Other alternative solutions, like in-situ bioleaching of stratiform copper ores, at Rudna, Poland (BIOMOre project) are in pilot stage. The automation in Kiruna has been developed improving the traditional mining, i.e. opposite trend to robominer. BIOMOre is more alike to the robominers concept, but the technology is not conventional extraction, but by bacterial leaching.

In many ways, these tests (and other on-going similar efforts) serve as good examples regarding the technical solutions and possibilities for a small scale robominer operation. There is a great number of other conditions, like elevated temperature, rock burst hazard, water, and lack of oxygen, which act as main barriers against traditional underground works. Robominers technology (supposing that economics allow) may open these environments for production.

Considering the above-mentioned circumstances and the advantages of the robominer technology to traditional mining, the following geological and mining scenarios can be set up:

- Operating and abandoned mines with known remaining unfeasible resources;
- Ultra depth;
- Small deposits uneconomic for traditional mining.

7.1 Operating and abandoned mines with known remaining unfeasible resources

In theory, the active or abandoned mines of traditional ore mining products would be favourable for the robominers technology because the operation can be serviced from the existing adjacent plants, and all the existing infrastructures could be adapted to the automated production. In these cases, the geological knowledge is generally satisfactory, and can be extrapolated with satisfactory precision from the former neighbouring operations.

With regard to the European ore deposits, such situation is probable, since a great number of occurrences have been stopped, suspended or closed without the full exhaustion of the mineralisation. Such existing resources may well be upgraded to reserves if the necessary investment is low, and the operation could be flexibly managed, as allowed by the manless automated small scale operation of the robotic miners.

Example for the scenario: Neves-Corvo

Neves-Corvo Cu-Zn mineral deposit is located in the western part of the Iberian Pyrite Belt (IPB), which extends some 230 km, stretching through Southern Spain into Portugal. IPB involves around 85 known deposits containing a mined + reserve tonnage of some 1.756 Gt of ore with 14.6 Mt Cu, 13 Mt Pb, 34.9 Mt Zn, 46 188 t Ag and 887 t Au (URL 6).

Neves-Corvo mineral deposit is classified as volcano-sedimentary massive sulphide (VMS) type, formed in an extensional tectonic regime from the Late Devonian to the Carboniferous. The host rock of the mineralisation is a rhyolitic-type volcanic, volcanoclastic and sedimentary complex. The volcanic activity occurred at moderate water depth in variably subsiding basins. Several syn- and post-ore modification events include gravity-driven mass transport processes and subsequent low-angle thrusting and asymmetric detachment folding, which shaped the present deposit.

Ore bodies in the deposit typically occur as lenses of polymetallic Cu-Pb-Zn massive sulphides (chalcopyrite, pyrite, galena, sphalerite) with additional Sn (cassiterite) mineralisation that formed at or near the seafloor in submarine volcanic environments. Mineral textures are complex due to the intergrowth between chalcopyrite-tetrahedrite-tennantite-sphalerite-pyrite, produced by multistage replacement phenomena. Sphalerite is frequently replaced by by chalcopyrite, tetrahedrite/tennantite and by stannite. The other principal sulphides include galena, bornite and arsenopyrite, with a wide variety of accessory minerals. The geology of the deposit is summarised in details in the reports of the H2020 project CHPM2030, as Neves-Corvo was a pilot site of the project (Ramalho et al. 2017, 2019).

The mine is operated by Somincor, a subsidiary of Lundin Mining. The operation is based on a number of ore lenses linked by zones of thin discontinuous mineralisations, forming an overall, shallow NE dipping, irregular, massive sulphide zone. The extent of this zone is about 1.8 x 3 km and locally, the ore lenses can be maximum 90 m thick (Newall et al. 2017).

Each of these bodies exhibit stockwork zones in the footwall host rocks and are located above the thickest pile of felsic volcanic rocks. They display distinct vertical and lateral zonal patterns of metals with Cu-rich sulphides predominating at the base, overlain by zinc-rich sulphides (if present) and 'barren' (lower grade) massive sulphides towards the top (Almodóvar 2019).

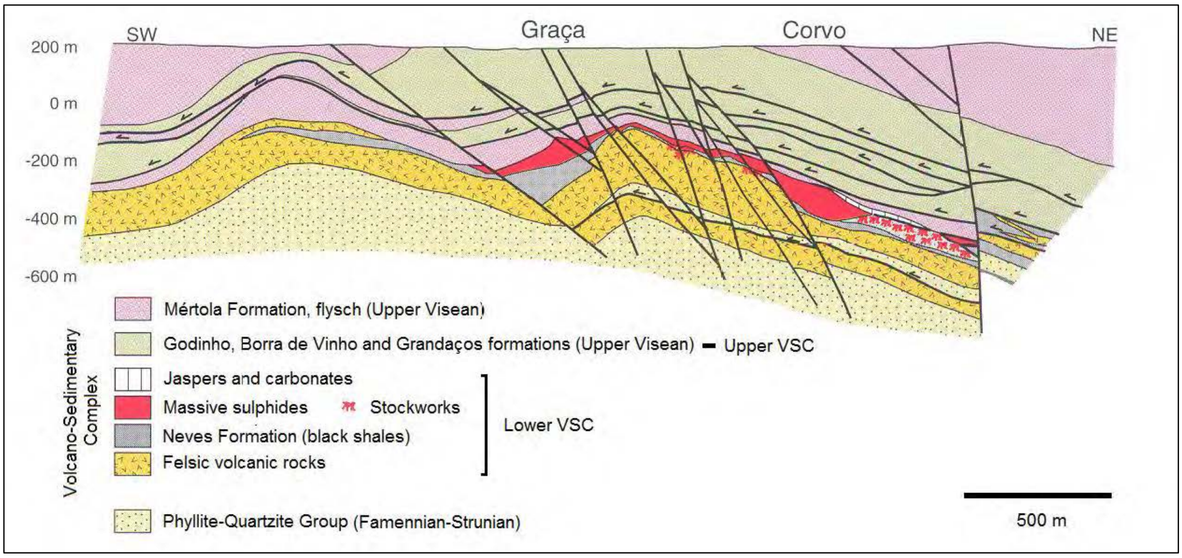


Figure 31: Neves Corvo general geological section, adapted from Relvas et al., 2006 (Ramalho et al. 2017)

Geometry of the ore lenses is well known due to the long mining activities *(Figure 31)*. They are relatively flat, extensive in two dimensions (600-1200 m × 500-700 m) and their thickness varies from 50 to 90 m. Exploration surrounding the mine has focused on the search for additional blind massive sulphide deposits. Exploration techniques include soil geochemistry, geological mapping, various geophysical techniques including airborne magnetics, residual ground gravity survey, airborne gravity survey, ground electromagnetic survey and 3D seismic survey *(Figure 32)* and exploration drilling (Ramalho et al. 2019).

Seven massive sulphide lenses have been identified comprising Neves, Corvo, Graça, Zambujal, Lombador, Semblana and Monte Branco. The base metal grades are segregated by the strong metal zoning into copper, tin and zinc zones, as well as barren massive pyrite. The massive sulphide deposits are typically underlain by stockwork sulphide zones, which form an important part of the copper orebodies.
It is assumed that non-economic sections connecting the known seven massive sulphide lenses offer good opportunity to introduce the robominer technology. Such relatively well-explored connecting zones are between Corvo, Zambujal, and Semblana deposits.

A possible option is to work on the known large orebodies using the traditional underground mining methods, while applying robominer technology in the connecting thinner segments, which would be uneconomic to develop for traditional extraction. Robominer automated stopes could be developed and serviced from the existing and operational underground haulage, hoisting, ventilation and energy supply systems. The mine has on-site ore processing facilities. The extracted product could be composited with the traditional mine products in a certain point of the processing flowsheet.

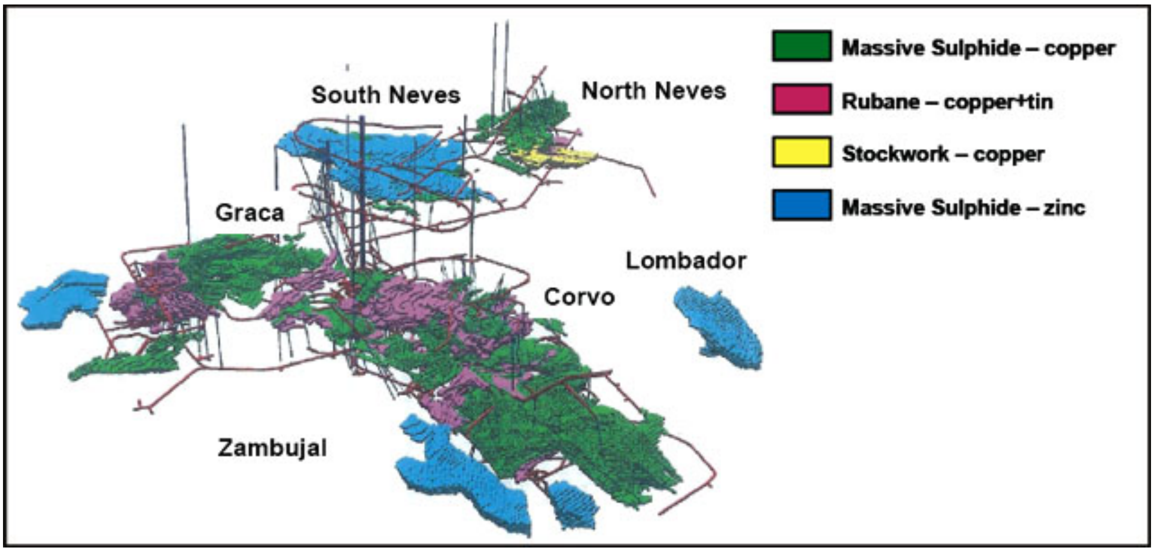


Figure 32: 3D model of the ore bodies (isometric view to NW) published by Somincor. Source: https://www.sec.gov/Archives/edgar/data/1377085/000120445908001113/p20.jpg

7.2 Ultra-depth

Excavating deeper underground is one way to extract more resources, as metal-rich mineral deposits exist well below the depth of traditional mining. However, going deeper incurs a set of technological challenges like geotechnical risk, energy consumption for ventilation, safety risk, etc., which makes mining uneconomical.

The term 'ultra-deep' means the depth below the level of traditional mining. The deepest mine on Earth reached 4 km depth (Mponeng Gold Mine in South Africa). In the EU, the deepest operating mine is about 1400 metres deep (Pyhäsalmi in Finland). In general, mineral deposits below 2.5 km are

considered 'ultra-deep' for conventional mining. However, in the EU, we can interpret the depth below the deepest mine, Pyhäsalmi as 'ultra-deep'.
We have detailed knowledge of the surface geology in many regions, but the amount and quality of information reduces with depth. To locate ultra-deep exploitation facilities requires considerable improvements in our understanding of the formation and distribution of mineralisation at depth. The target ore zones should be well identified in terms of geometry, internal structure and mineralogical composition. Surface and shallow-depth observations, as well as geophysical and geochemical data from the deeper portions help us in modelling the ultra-deep continuation of some mineralisation types. Specific deposit types have subvertical or subhorizontal elongation, and relatively predictable geometry. In most metallogenic belts in Europe, mineralisations of many types continue to depths beyond those previously targeted by commercial exploitation.

Example for the scenario: Kupferschiefer, Fore-Sudetic Monocline

Kupferschiefer is a continent-wide formation, dominantly bituminous marly shale, which hosts enormous metal accumulations. It is a stratiform sediment hosted copper (SSC) type deposit. The easternmost manifestations are in Upper Silesia (Lubin, Poland), whilst westwards it continues through Germany (Lausitz, Mannsfeld, Richelsdorf), and is also known in England (Alderly Edge) (Borg et al. 2012). Its deepest known intersected position in the Permian Zechstein Basin is under the North Sea at 4000 m depth (Haslam, 1982). About 80 % of the known Kupferschiefer mineralisation lies below depths where current exploitation takes place. This deposit type has extremely persistent horizontal extension, predictable geometry and very high concentration of metals per unit area.

Kupferschiefer was formed at the end of the Variscan (Hercynian) orogenic period. The post-orogenic subsidence of the Zechstein Sea in North Central Europe and England (Central European Basin System) and consequent transgression has led to the sedimentation of the thin (0.3–4 m), but widely distributed bituminous marl-sandstone-limestone-shale layers, which are enriched mainly in base metals (Zientek et al. 2015).

The main metals are Cu, Pb and Zn in small grained (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 white and red coloured, barren sandstone, and is covered by Zechstein limestone or dolomite *(Figure 33).* The initial stratiform mineralisation of low concentration (~100 ppm) was enhanced to some percents of base metals by late diagenetic processes dated to the Early Triassic (Muchez et al. 2005), or by even later mineralisation processes (Borg et al. 2012).

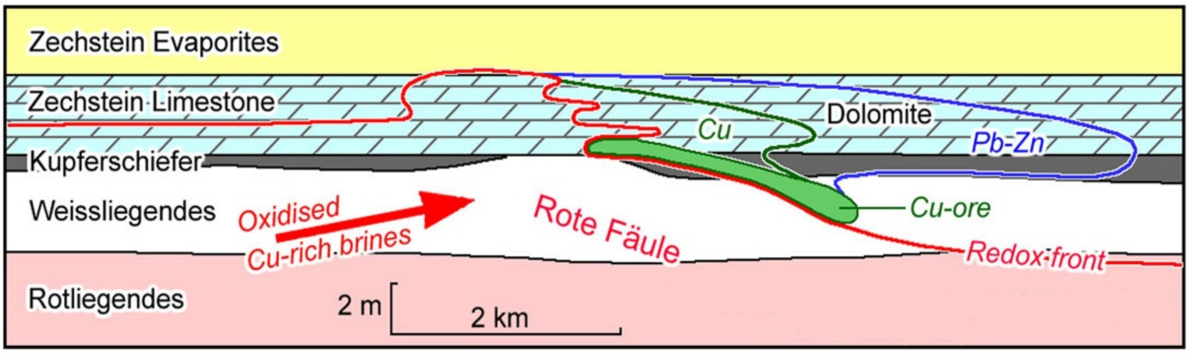


Figure 33: Schematic cross section (exaggerated vertically) of the Kupferschiefer mineralisation showing the relationship between secondary geochemical processes, metal zoning and ore formation Source: Borg et al. 2012

The mineralisation is of disseminated and replacement type. Mineralised bodies are always associated with red coloured barren sandstone ('Rote Fäule'). Locally, the mineralised horizons (extending to more than one levels of the succession) can reach the thickness of 50-80 m (Borg et al. 2012, Zientek et al. 2015). The burial depth can reach several kilometres (Bechtel et al. 2000, Oszczepalski & Speczik 2011).

Mining started in Germany at outcrops of the formation, but those deposits are already exhausted. Prospective and mining areas were summarised by Zientek et al. (2015). Currently, there are operating mines in Poland (Rudna, Sieroszowice, Polkowice, Lubin-Małomice, Głogów Głęboki-Przemysłowy and Radwanice-Gaworzyce). The Polish mines are situated in the area of the Fore-Sudetic Monocline *(Figure 34)*.

According to the data by the Polish Geological Institute, registered economic and subeconomic resources are 563.2 and 809 Mt of ore, containing 8.1 and 13 Mt Cu and 22,400 and 41,000 t Ag, respectively (URL1). Available resources are already at great depth. The operating shafts of the Rudna mine (KGHM Company) reach from 941 to 1244 metres, at Głogów Głęboki-Przemysłowy the deposit is followed down to 1385 m (URL2). Subeconomic reserves lying NE from the operating mines are in still greater depth. At Rudna, the productive layers are mostly sandstone beds, and the thickness of these exceeds 3 m for more than 70% of the resources.

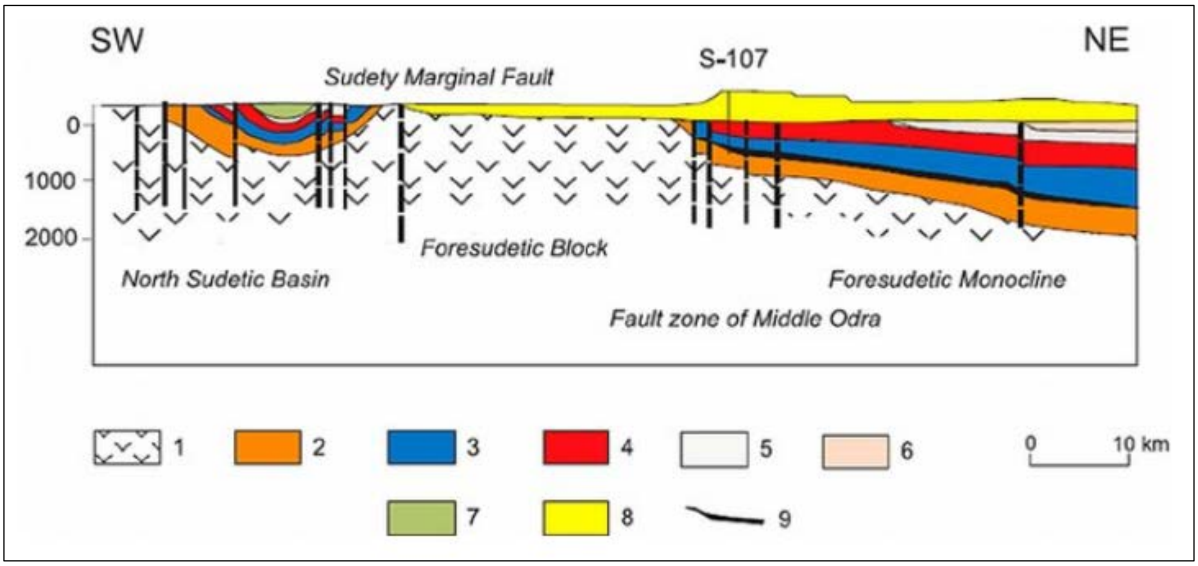


Figure 34: A geological cross-section across the North Sudetic Basin (the old copper ore basin area), Fore-Sudetic Block and the Fore-Sudetic Monocline (the LGOM Copper Ore Basin). 1: Crystalline basement, 2: Rotliegendes, 3: Zechstein, 4: Bunter Sandstone, 5: Muschelkalk, 6: Keuper, 7: Upper Chalk, 8: Cenozoic formation, 9: ore deposit. Source: Bauer et al., 2015

In the Fore-Sudetic Monocline, Cu-Ag mineralisation occurs in the upper part of white sandstone, the copper-bearing shale and the lower part of overlying clayey dolomite (Bartlett et al. 2013). An analogous sequence of Cu- and Ag-bearing sediments is also confirmed in deep zones (2000-4000 m) in the Polish Lowlands (Zieliński et al. 2017). All these sediments dip towards NE at a slight angle of 1-6 degrees.

The total thickness of copper-bearing layers in the area commonly varies from 1 to 7 m (in average commonly 3-4 m), but at some places it can reach 17 m. These layers include (from below) white sandstone, copper-bearing shale, clayey dolomite and 'streaked' dolomite. The thickness of the copper-rich shale (the most enriched unit of the copper-bearing layers) is generally 0.4-0.6 m but can reach max. 1.7 m. The Cu content in these layers varies from 5 to 11%. The organic content is high (3-15%). (Bartlett et al. 2013; Konopacka, Zagożdżon 2014).

The ore is currently processed in the KGHM's plants with average yield of 89% Cu and 86% Ag. The main stages of processing are crushing and sieving (closed loop), milling and classification (closed loop), flotation (initial, main and cleaning), thickening, filtration and drying (Bartlett et al. 2013).

The potential resources of copper and silver ores in the deeper sections of the Fore-Sudetic Monocline are enormous. Prospective areas with speculative resources of Cu and Ag are identified by drillholes down to the depth of 4000 m. Detailed data on the explored ultra-deep sections of the ore deposit are not public (or only partly available) but we can assume that they are similar to those at the exploited levels.

With increasing depth, the exploitation would be cheaper by automation and the cross section necessary for access and transport of the materials could be decreased. Robominers technology could also make the production of thin mineralised beds economic, which are possible to follow for large distances. This would enhance the amount of economic reserves significantly.

7.3 Small deposits uneconomic for traditional mining

For hundreds of years, most of the world's ore production came from vein deposits. Mines had traditionally operated in a narrow-vein environment, simply because the technology of that time would not allow anything more extensive. Waste-rock handling was minimised as mining was highly selective, keeping profitless dilution at rock-bottom.

With the increasing demand for metals, and the development of the extraction technologies, the interest turned to the large-tonnage, lower-grade deposits, as these are much more common, easier to access, operate for longer time and can guarantee the return of the high capital investment.

In Europe, there are a large number of small vein-type mineral deposits, which have high concentration of metals. However, these deposits are considered non-economic, as they are too small to be mined by conventional methods. The main problem is the low economic return, but environmental issues or health and safety problems also mean obstacles. The robominers technology provides solution for these problems and sub-economic resources can become viable.

Example for the scenario: United Downs project, Cornwall

The United Downs project in Cornwall, UK covers a newly discovered high-grade copper-tin vein-type deposit of unknown extent, in the south-west England mineralisation province.

South-west England is a mining region with a very long history of exploitation for tin, copper, tungsten, and other metals as well as kaolin and other industrial minerals. The most intensively mined districts are in central and western Cornwall, where tin and copper were the principal metals produced by many hundreds of mines, mostly in the 18th and 19th centuries but a few into the late 20th century. Of these, South Crofty mine has been the subject of a number of attempts at reopening, currently by a Canadian-listed company Strongbow Exploration. The lease includes areas of several abandoned mines but also some previously unexplored areas, where significant reserves of tin and copper have been identified.

Strongbow Exploration also owns mineral rights over several other areas in the same mineral region. One of these is an area named United Downs.

United Downs is located approximately 8km east of South Crofty *(Figure 35)* and lies within a densely mined district, historically referred to as Gwennap. Gwennap was the richest copper producing region in Cornwall (and the world) in the 18th and early 19th centuries, and at that time was referred to as “the richest square mile on earth”. However, even in this 'square mile' there were areas that were never explored. 18th and 19th century mineral exploration did not use deep drilling but usually relied upon following known veins, at surface or by underground development.

In April 2020, Strongbow Exploration reported the discovery of a new zone of a high-grade copper-tin mineralisation located in a previously unmined area between the historic United Mine and Consolidated

Mines at United Downs. The deposit, by chance, was never previously found, in an area between previously exploited and now abandoned mines.

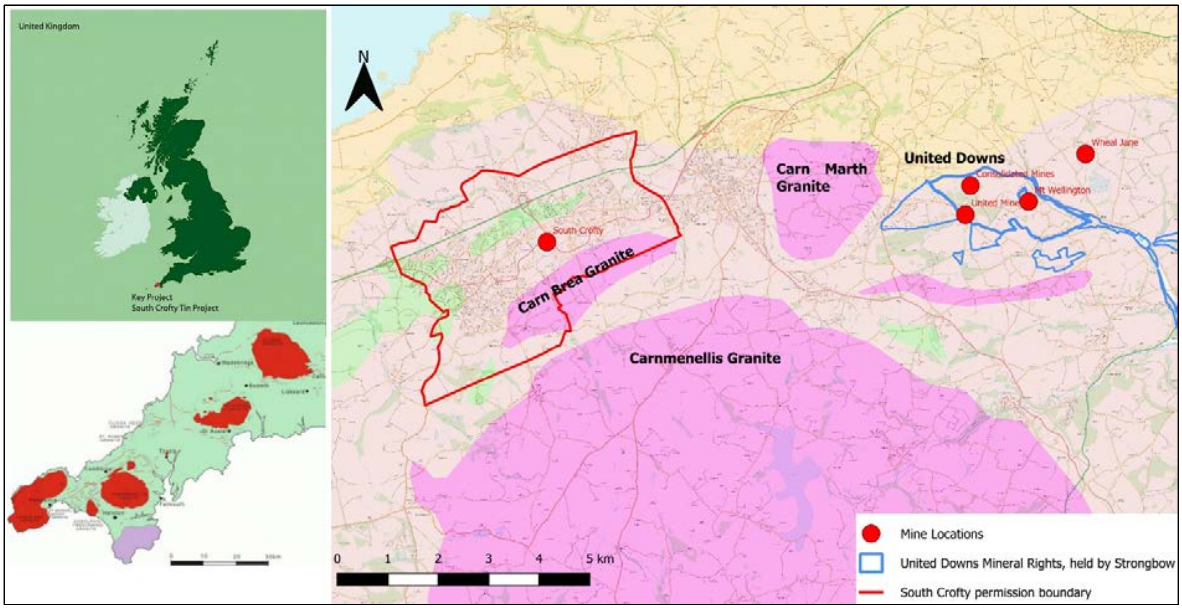


Figure 35: Location of the United Downs copper-tin project.
Source: https://www.strongbowexploration.com/projects/uk/united-downs/

The discovery was made in one drill hole GWDD-002, drilled by Cornish Lithium under a joint venture agreement with Strongbow. Two diamond drill holes have been completed, for a total length of 1,858m and at the time of writing, only results from part of diamond drill hole GWDD-002 have been reported so far. It is a 'semi-massive' sulphide deposit that has been intersected in drillholes at around 100m depth with grades of 7.46% Cu and 1.19% Sn over a drilled interval of 14.7 metres. The mineralisation is similar in style to that mined in the 20th century at nearby Wheal Jane and Mount Wellington mines, and copper grades are similar to those historically recorded at the adjacent United Mine (Figure 36).

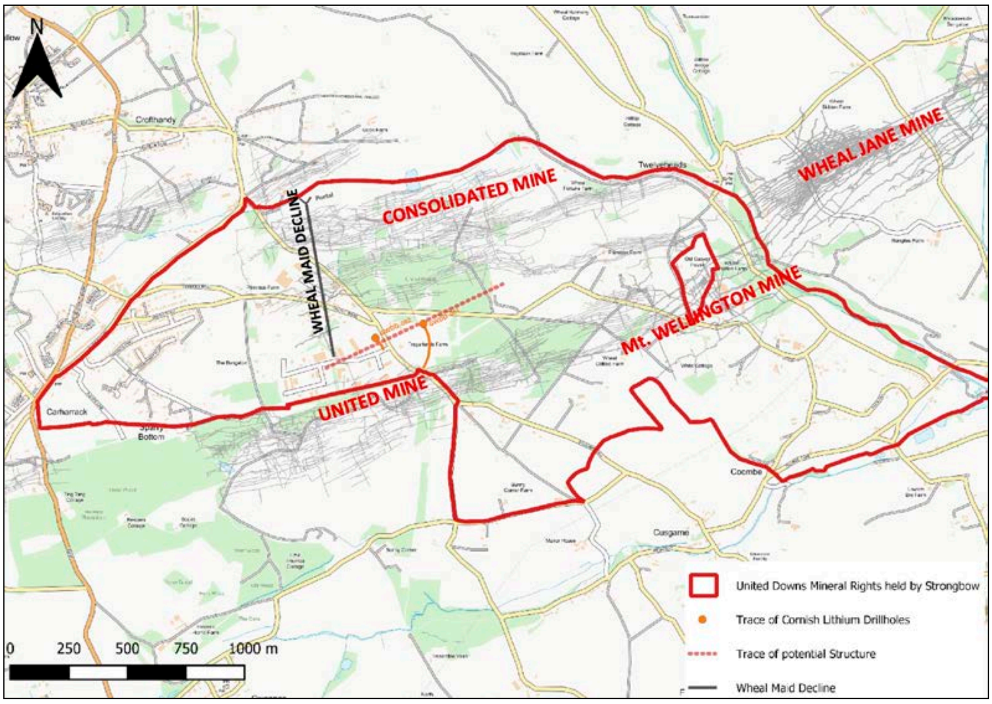


Figure 36: United Downs area showing location of the Wheal Maid decline and likely orientation of the newly discovered deposit. Source: https://www.strongbowexploration.com/projects/uk/united-downs/

The extent and geometry of this deposit are not yet known, though it is believed to be a vein deposit similar to those in known mines in the surrounding area. Although the drilled intersection was over 14 metres in length, the true thickness is probably much less as the drillhole would have intersected it obliquely.

Currently there is only one intersection, so the true form, orientation, and extent of the deposit are all unknown. However, the style of mineralisation in this region is fairly consistent (Dines 1956, Moissenet, 1877): steeply dipping tabular veins trending a few degrees north or south of east-west. The detailed structure of these veins can be quite complex, reflecting multiple phases of opening and mineralisation, frequently with brecciation of the vein material and mixing with wall rocks. Branching of veins is also common, as illustrated by Moissenet *(Figure 37)*.

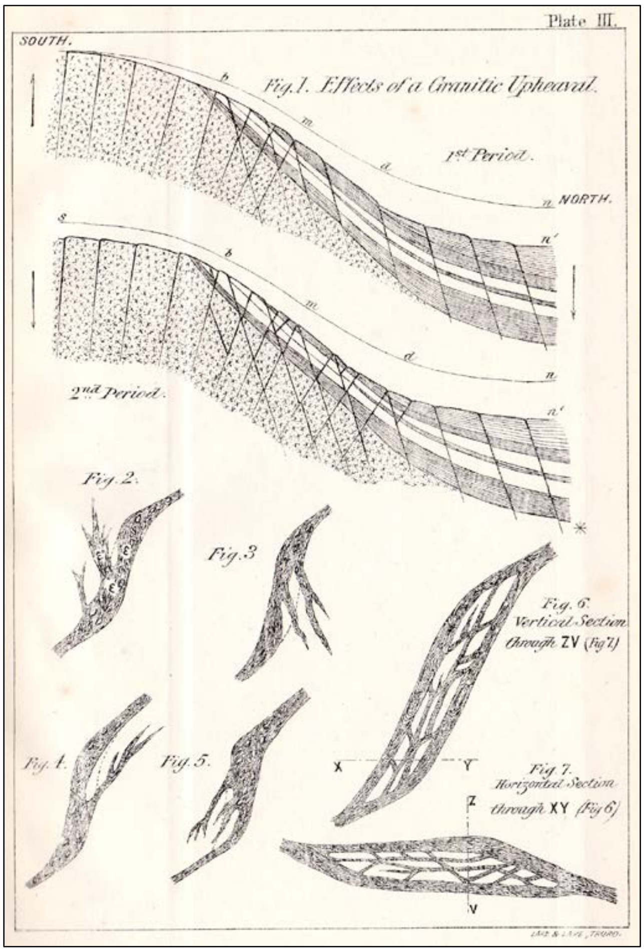


Figure 37: Typical vein structures in the south-west England mineral province. Source: Moissenet, 1877

The United Downs project covers, or is located immediately adjacent to, four former copper and tin producing mines: Consolidated Mines and United Mines to the west; and, Mount Wellington and Wheal Jane Mines to the east. The main mineralised structures in all four mines trend ENE and dip steeply to the north. All of the mineralisation exploited historically is related to either quartz veins or quartz-tourmaline veins hosted within Devonian metasedimentary rocks that overlie the early Permian granite intrusions.

At the nearby South Crofty Mine, copper-tin-zinc-tungsten mineralisation hosted within the Devonian metasediments passes into tin mineralisation at depth as the mineralised vein-like structures pass into the underlying granitic host rock. The same zonation potentially exists at United Downs, where only the metasediment-hosted mineralisation has been exploited to date. The underlying granite, which is a target for further tin mineralisation, was encountered in hole GWDD-002 between 300 and 600m and again at 700m vertical depth.

The nearby Wheal Jane mine was discovered and developed into a modern mine in the late 1960s, initially by Consolidated Goldfields, and thereafter by Rio Tinto Zinc. Mining activities at Wheal Jane ceased in early 1991, due largely to the Tin Crisis of 1985, but processing of South Crofty ore continued until March 1998 when ongoing low tin prices forced its eventual closure.

As part of the intense exploration period that Cornwall enjoyed between the 1960s and 1985, an underground exploration drive was developed during the 1980s westwards from Wheal Jane through Mount Wellington mine at depth. An exploration decline (the Wheal Maid decline, *Figure 36*) was developed to explore for tin mineralisation similar in style to that which was exploited in Mount Wellington and Wheal Jane mines. This exploration work was stopped after the tin price collapse in 1985, despite the great promise for the discovery of polymetallic mineralisation. Neither of these exploration drives intersected the newly discovered deposit.

In case that this is found to be only a small deposit (which is entirely possible considering that it was not discovered in any of the surrounding mines), even if high-grade, it would probably be uneconomic to dewater either the Mount Wellington Mine or the Wheal Maid decline for conventional mining. However, it would be ideally suitable for robotic extraction by the robominers technology, using ore-following methods.

Considered as a site for potential exploitation by robominers, starting at a known location, with possible access through the existing Wheal Maid decline or the exploration drive in Mount Wellington mine, this could be exploited by extraction of the whole massive sulphide vein, and an exploitation mine-plan geometry for a steeply dipping tabular deposit. De-watering may not be necessary for robotic operation. If, as is possible, the vein is greater than 1 metre in thickness, little or no waste need be mined, and an open stoping method could be adopted. Supports would probably need to be provided, or pillars left unmined to support the hangingwall, as collapses were common in other mines in the same district, exploited by open stoping with or without backfill, thus requiring substantial supports.

8 EUROPEAN OTLOOK – POTENTIAL TARGETS

The aim of this chapter is to provide a general picture about the distribution of ore deposits in Europe. In the following sections, the main occurrences are arranged according to the tectonic (metallogenic) provinces of the continent. These deposits cover all described scenarios discussed in Chapter 7. Several references are listed, which may help in collecting detailed data if a given deposit is selected as a potential pilot site for the robominers application.

8.1 Metallogenic overview

Metallogeny is the study of the genesis of ore deposits, with emphasis on their relationships in space and time. Geographically, the deposits are unevenly distributed, but deposits of specific metals or genetic types, or deposits formed in a certain epoch of the Earth history can form regional clusters. These clusters are called metallogenic provinces. However, if a province is defined by a mineral association (e.g. Iberian Pyrite Belt), it does not mean that 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, consequently, metallogenic provinces are determined best by the tectonic units. In this overview, we will follow a regional grouping of the metallogenic provinces and focus our attention to Europe without the eastern areas covered by Russia and other post-Soviet states, which are not members of the European Union.

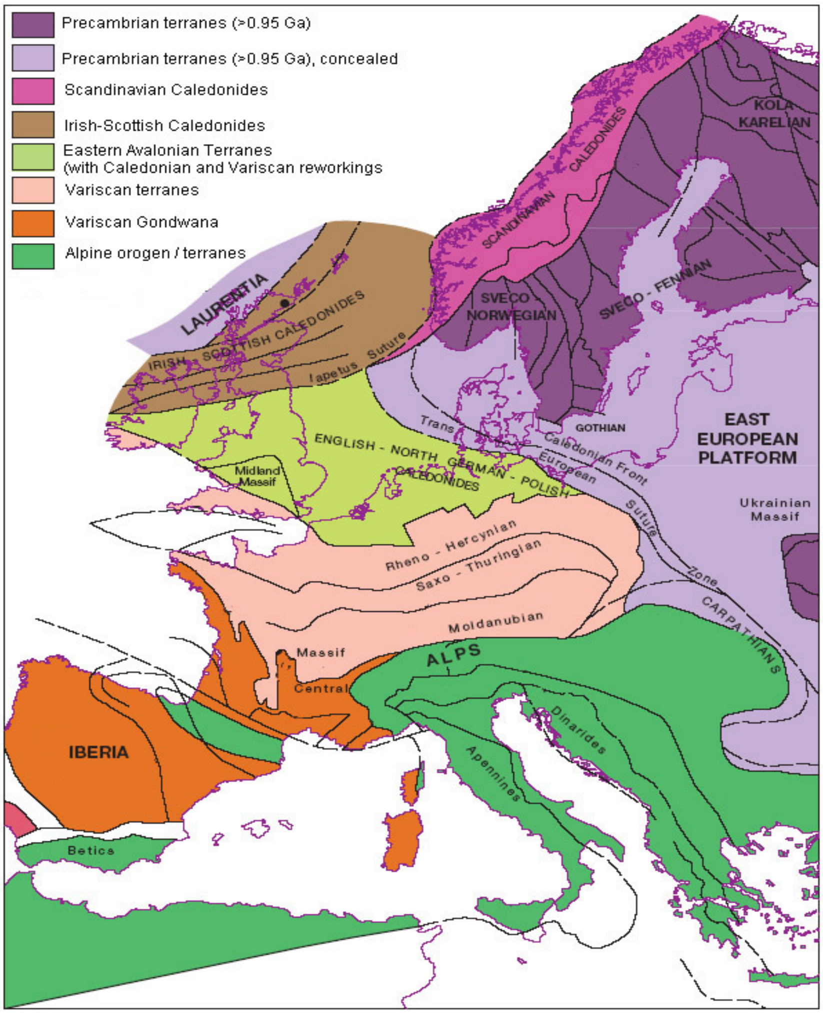


Figure 38: Major tectonic units of Europe. Source: Plant et al., 2005

According to the tectonics of Europe (Blundell et al. 2005, Plant et al. 2005), four large tectonic (and overlapping metallogenic) provinces can be distinguished. The provinces include a cratonic region and three orogenic belts *(Figure 38)*. Terrains of the orogenic belts can be found not only in Europe but also in other continents. In the list below, only the European areas are mentioned:

1) The *East European Craton* is the ancient core of the continent, comprising the Fennoscandian or Baltic Shield in the northeast and some other shield units in the east, dominated by Precambrian rocks and deposits.
2) The *Caledonian orogeny* produced the oldest mountain system in Europe formed in the Early Paleozoic. Within Europe, remnants of this ancient mountain system are preserved mostly in the north and northwest area of the continent (Scandinavia and the British Isles), in fragments of the Armorican and Bohemian Massifs in the south and southwest, and also in the south part of Britain.
3) The *Variscan* (also called Hercynian) orogeny in the Late Palaeozoic strongly overprinted parts of the Caledonian formations. Terrains of the Variscides are distributed in a large part of Europe, from SW Ireland to Poland, represented in SW England, the Ardennes, the Massif Central, the Harz Mountains, and the Bohemian Massif. The south-southeast parts of the Variscan system are overprinted by the Alpine orogeny.
4) The *Alpine* orogeny was characterised by the closure of the Tethys Ocean in the Mesozoic and Cenozoic era (still ongoing process), producing the formation of the large mountain chains of West, South, Mid- and East Europe, also continued throughout Asia.

8.2 Fennoscandian Shield

The Precambrian processes and ore deposits of this province were summarised by Weihed et al. (2005) and Stephens & Weihed (2020).

Denudated Archean granitoids of the shield area contain no noteworthy deposits of any ores but may occasionally host diamond and orogenic gold. In the greenstone belts, layered mafic intrusions host small Ni, Cr, Cu and PGE deposits, including the *Kemi* chromite as a single major one (Alapieti et al. 1989).

In the Lapland granulite belt Ti-Fe, Cu-Ni deposit (*Lovno-ozero*) and Au-PGE mineralisations occur (Rundqvist & Sokolov 1993); at *Bjørnevatn* (Norway) BIF type iron ore is mined. At the west and south border zone, the Proterozoic Svecofennian Orogenic Belt contains the world-class volcanogenic, stratiform, apatite bearing iron-oxide (magnetite and hematite) deposits of *Kiruna* of Norrbotten region, Sweden, also enriched in REE (Frietsch & Perdahl 1995), and several smaller but important ones both in the *Norrbotten* and *Bergslagen* regions of Sweden (Slagstad et al. 2016).

Polymetallic (Cu, Zn, Pb, Co, Ni, Ag and Au) sulphides in VMS, stratiform, porphyry and other hydrothermal vein systems are widespread in Sweden (e.g. *Skellefte* district), in Finland (*Outokumpu, Pyhäsalmi*) and at the *Lake Ladoga* in Russia.

Magnetite dominated skarn ores are often attached to the previous types. Late orogenic alkaline intrusions due to intracratonic rifting also produced skarn (e.g. *Bastnäs*) and pegmatitic (e.g. *Ytterby*) ores of REE and rare elements (like Li, Be, B, W, Nb, Ta). The Late Proterozoic Sveconorwegian Belt contains no significant mineralisation, an orthomagmatic Ti deposit at *Egersund* (SW Norway) can be mentioned.

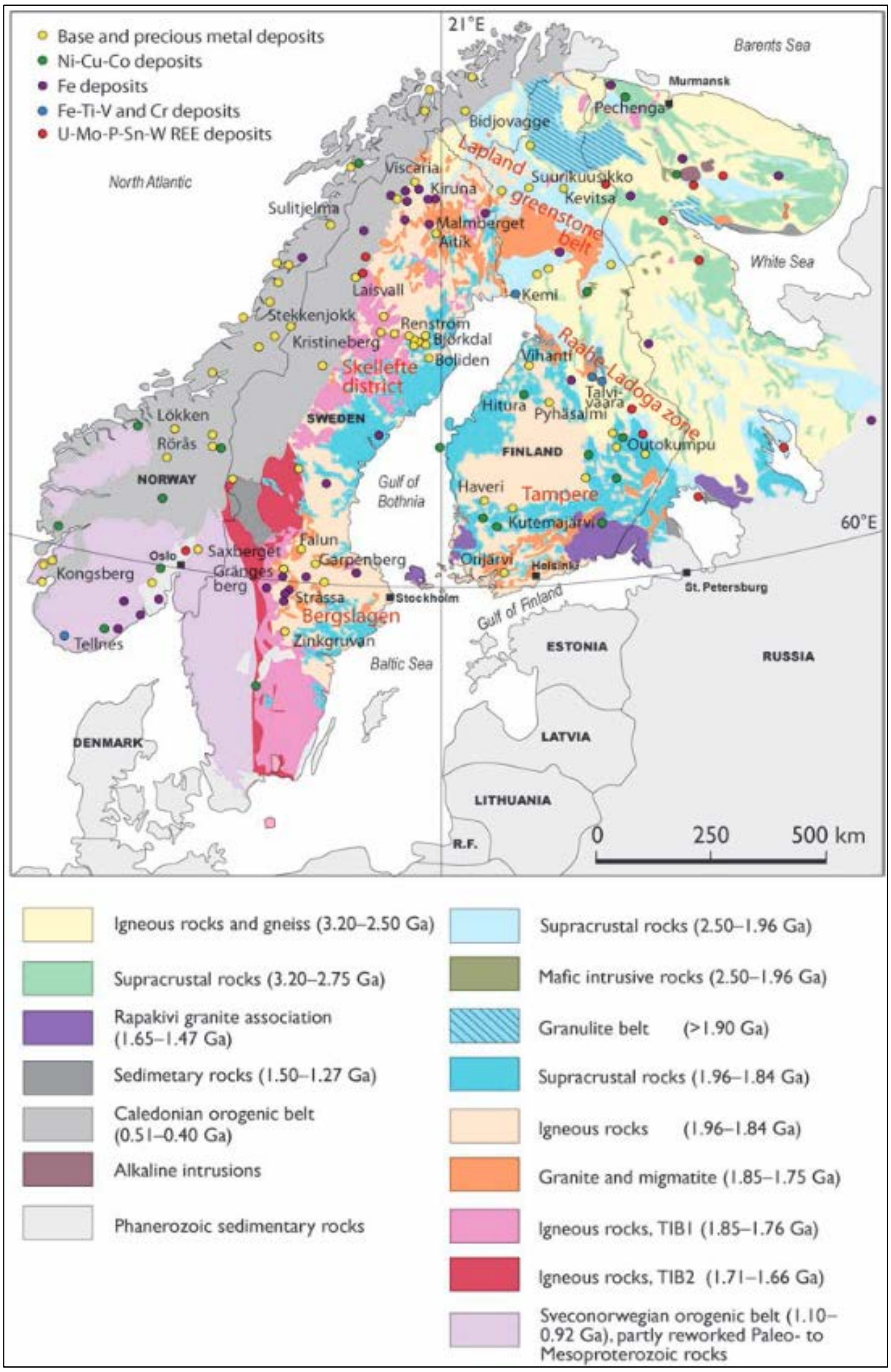


Figure 39: Simplified geological map of Scandinavia with the locations of the major ore deposits. Source: Weihed et al., 2008, https://www.diva-portal.org/smash/get/diva2:987130/FULLTEXT01.pdf

Large-scale mining of the province dates to the 13th century, when professional operations of the *Falun* polymetallic sulphide ore started in Bergslagen region, Sweden (Kampmann et al. 2017). Falun was the largest copper supplier mine of the continent up to the 17th century. Base metal production of Sweden is still significant, mainly at *Boliden*. Besides the iron ores of Norrbotten, currently mined by the LKAB, the province (Finland and Sweden) also provides most of the current gold production of the European Union, with the *Kittilä* open pit and underground operations (Finland) on an orogenic pyrite-arsenopyrite hosted gold deposit as the biggest mine (Wyche et al. 2015). Locations of the major ore deposits in the Fennoscandian Shield are shown in *Figure 39*.

8.3 Caledonides

8.3.1 Scandinavia

The Caledonian deposits of the Scandinavian Peninsula were summarised by Grenne et al. (1999). The pre-orogen formations include stratiform and stratabound base metal (Zn-Pb-Cu) sulphide deposits (e.g. *Bleikvassli, Mofjellet*) and magnetite-hematite Fe ores (e.g. *Dunderlandsdal* region). Alkaline and carbonatite magmatism related to the Early Cambrian rifting produced the *Fen Complex* with Fe, Nb, REE and apatite deposits, and also orthomagmatic Cr and Ni-Cu-PGE mineralisations.

The passive margin of the continent Baltica during the Cambrian was dominated by the sedimentation of the bituminous and pyrite-rich, 20-60 m thick *Alum Shale* with widely distributed U, Mo, Ni, V, As, Zn, Cd and Pb enrichment. In the second half of the 20th century it was used as uranium ore. It's known in outcrops and shallow setting, but in the southern part of the distribution area (in Denmark and Southern Sweden) hydrocarbon explorations followed it down below 7 km in the Danish-Norwegian Basin (Lassen & Thybo 2012). These deeper sections are in line with the parameters of the 'ultra-deep' scenario. The thickness of the Alum Shale can reach 100 m with tectonic repetitions.

Zn- (e.g. *Stekenjokk-Levi*) and Cu- (e.g. *Løkken*) dominated VMS deposits were formed by the Ordovician-Silurian subduction related magmatism. Other ore types of this magmatism are not economically significant. Granodioritic plutons and their country rocks may host some stockwork Cu-Mo, skarn and pegmatite Zn-Pb-Cu, Mo and W mineralisations. Late mafic intrusions produced Ni-Cu deposits (e.g. *Bruvann, Råna*) and stratabound base metal sulphides (*Røros* and *Sulitjelma* regions).

In the subsequent Devonian collision stage, the development of two deposit types was significant: sandstone-hosted (e.g. *Laisvall*) and carbonate-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.

Significant post-Caledonian deposits are present in the province, partly in the basin of the North Sea. Late Palaeozoic rifting related alkali intrusions in the *Kola Peninsula* host apatite, Nb and REE deposits (Goodenough et al. 2016). Most of the current large-scale mining operations of the Scandinavian part of the Caledonian province take place here. The igneous complex of the *Oslo Graben* contains Ag-bearing base metal veins and disseminated Cu-Mo mineralisation in felsic igneous rocks. This complex also includes Au, Ag, Pb, Cu, Zn mineralisation in quartz veins and iron skarn ore bodies (Bjørlykke et al. 1990). Contemporaneous volcanic formations can be found in the Denmark and Skagerrak Grabens in the Central North Sea (McCann et al. 2006).

The main ore deposits of the Scandinavian Caledonides are indicated in *Figure 39*.

8.3.2 The British Isles

The Caledonian deposits of the British Isles were summarised by Plant et al. (1999), Rice (2002) and by the BGS (Colman & Cooper 2000). Although there are hardly any world-class ore deposits in the region, several small ones are known and were subject of mining in the past *(Figure 40).* Significant operating mines of this part of the Caledonian province are mostly in *Ireland* (lead, zinc and silver production are among the largest in Europe), but several historical ones for various ores are found elsewhere.

Subduction related deposits are of minor importance, but there are prospective regions (Hollis et al. 2014). There are several intrusion or volcanism-related vein type and stratiform base metal deposits. Porphyry-type Cu-Mo-deposits are minor, but abundant in the province. Cu-Ni *(Aberdeenshire)* and PGE-bearing chromite *(Shetland Ophiolite Complex)* is also present attached to mafic intrusions (Rice 2002). Carbonate-hosted stratabound base metal deposits are important from the collisional stage of the orogenic system (e.g. *North Pennine Orefield*) and in attached basins (e.g. *Navan* and *Silvermines* in Ireland). MVT or Irish type Pb-Zn deposits occur also in the North Sea basin, explored for hydrocarbons (Baines et al. 1991).

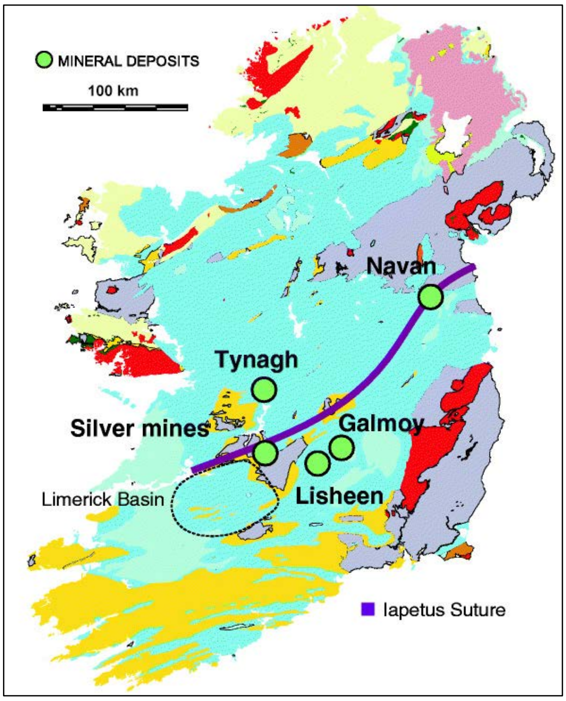


Figure 40: Location of Navan and Silvermines in Ireland. Areas of the Caledonian orogeny are indicated in purple. Source: Davidheiser-Kroll et al., 2014

8.4 Variscan Europe

8.4.1 Iberian Peninsula

Spain and Portugal are both historically and recently significant producers of base metals in Europe, mostly coming from world-class deposits of Variscan terranes.

Late Devonian-Early Carboniferous rifting-related volcanism produced several VMS deposits. The 240 km long and 70 km wide *Iberian Pyrite Belt* is hosted by a volcano-sedimentary sequence either in black shale or lying on the top of rhyolitic volcanics. The main metals are Cu, Pb, Zn, Ag and Au, but in certain deposits Sn, Bi, and Co may also be enriched. Small Mn oxide deposits are also present. Estimated ore resources of the known world-class deposits *Rio Tinto, Tharsis, Aznalcóllar-Los Frailes, MasaValverde, Sotiel-Migollas, La Zarza* (Spain)*, Neves Corvo* and *Aljustrel* (Portugal) exceed 1700 Mt altogether (Tornos et al. 2009) *(Figure 41)*.

The southwestern *Iberian Massif* also contains VMS base metals (Cu, Pb, Zn), barite and Zn-Pb sedex deposits. Granite-related Sn-W and base metal-bearing veins, skarn ores, Cu-Ni magmatic ore bodies and orogenic Au mineralisation are also present. Orthomagmatic Fe-Ti-V and Ni-Cu-PGE mineralisation developed at *Aguablanca*. Pb-Zn- and Cu-dominated lodes, Hg replacements and uranium-bearing veins occur without known magmatic sources (Tornos et al. 2004).

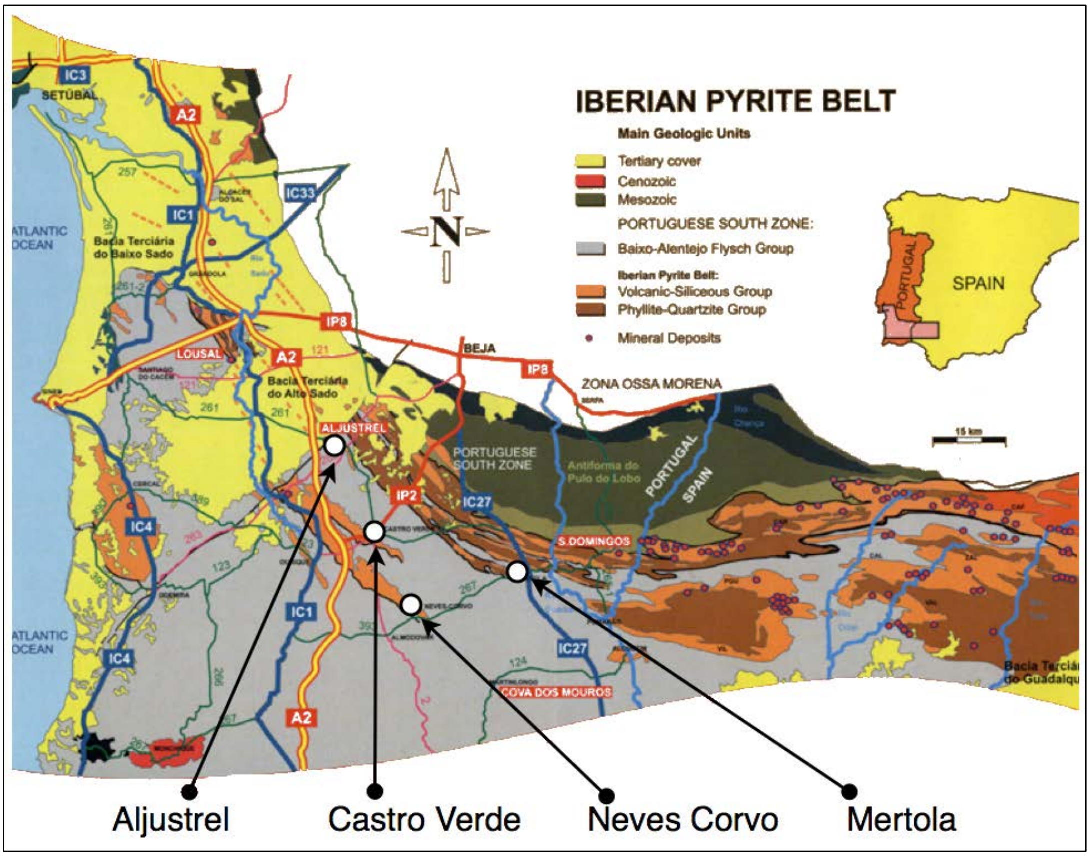


Figure 41: The Iberian Pyrite Belt with the location of the main mining sites. Source: https://en.wikipedia.org/wiki/Iberian_Pyrite_Belt

The Central Iberian Zone contains two world-class deposits: the quartzite-hosted, stratabound and stockwork-type *Almadén* Hg deposit (Palero-Fernández et al. 2015) and the *Panasqueira* vein-type Sn-W deposit. Further pegmatitic and other granite-related hydrothermal Sn-W deposits and several vein type gold deposits are present in the zone. In Galicia, Li-bearing pegmatites and Sn-W veins are attached to granite, while disseminated and massive Cu-Fe-base metal sulphides to metamorphosed ophiolitic complexes (Badham & Williams 1981). Gold veins also occur in sandstone in the *West Asturian-Leonese Zone* (Tornos et al. 1997).

8.4.2 From France to Poland

This wide region, although its ore mining is abandoned mostly, is rich in historic, traditional mining districts like Cornwall in England or the Harz and the Ore Mountains (Erzgebirge) at the German-Bohemian border *(Figure 42).* Major recent mines are in Poland exploiting world-class Kupferschiefer related and MVT base metal ore deposits, with the largest copper reserves in Europe. Small scale operations still have perspectives on deposits exploited by the traditional mining methods.

The majority of the important deposits are linked to granitic intrusions. In the *Armorican Massif*, granitic intrusions contain Sn-W mineralisations. In *Bohemia*, VMS polymetallic ores, in the *Central Bohemian Metallogenic Belt* orogenic and intrusion-related gold veins and stratiform Cu-Zn-Au sulphide mineralisations are present. BIF-type Fe-V-U and pyrite-bearing black shale locally enriched in Ni, Zn, Mo and Cu sulphide mineralisations are hosted by metasedimentary successions (Mrázek & Pouba 2013).

SEDEX-type Zn-Pb deposits in *Meggen and Rammelsberg* are included in formations formed during pre-Variscan rifting. Base metal mineralisation occurs in several deposits (e.g. in *Cornwall*). In Armorica

(*Bodennec* and *La Porte-aux-Moines*) and in the Massif Central (*Chessy* and *Chizeuil*) massive sulphide and black shale hosted Pb-Zn-Cu deposits were mined; these are similar but smaller deposits than in the Iberian Pyrite Belt (Lescuyer et al. 1998).

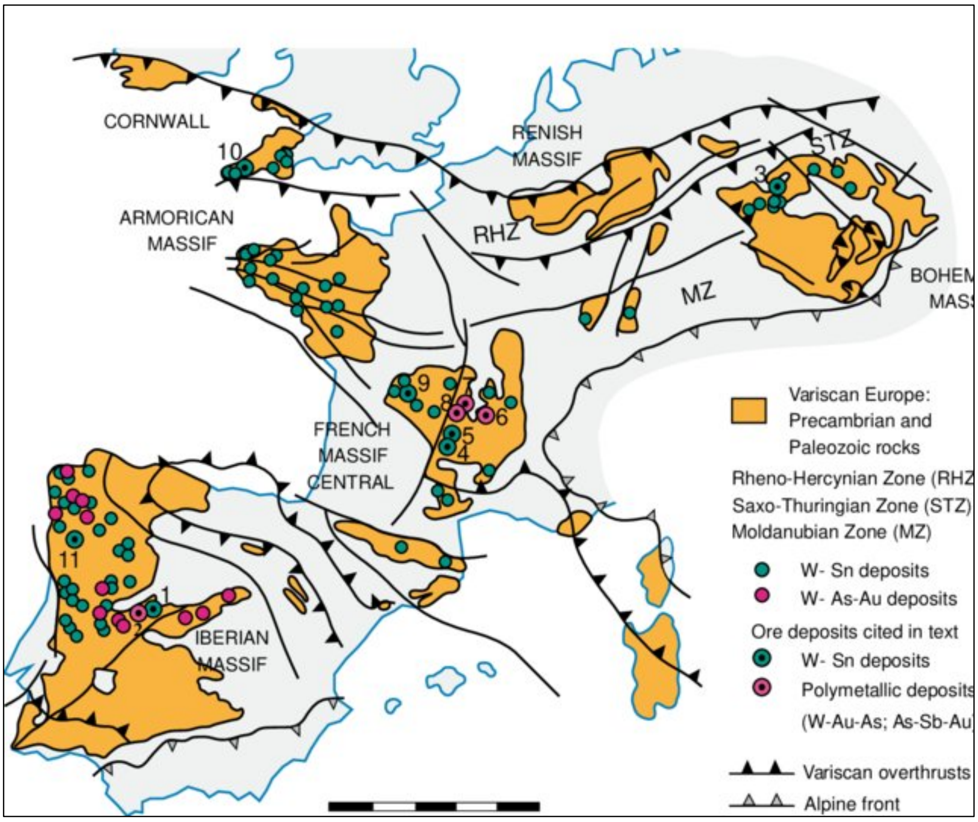


Figure 42: Map of the Variscan belt in Central and Western Europe with major W-Sn and some polymetallic deposits. Iberian Massif (1: *Los Santos*; 2: *El Cabaco*; 11: *Carris*), Bohemian Massif (3: *Gottesberg*), French Massif Central (4: *Enguialès*; 5: *Leucamp*; 6: *Brioude-Massiac*; 7: *Pointgibaud*; 8: *Labessette*; 9 *Vaulry*), Southwest England (10: *Cornwall*). Source: timón-Sánchez et al., 2019

In metamorphic successions and granitic intrusions, many vein and stockwork deposits are present. Polymetallic deposits were exploited at several places of the *Erzgebirge* or *Krušné hor*y (e.g. *Jáchymov* Ag and U ores), in the *Central Bohemian Mobile Zone* (e.g. *Příbram*), and in the Harz Mts. (e.g. *Andreasberg* Ag-Pb-Zn-Cu deposit) (De Vos et al. 2005). Hydrothermal mineralisations, which cannot be linked to magmatic formations also occur in several places: Pb, Zn, Sb deposits in *Armorica* (e.g. *La Lucette*), Au, Cu, As, W, Bi deposits (e.g. *Salsigne*) and in the *Massif Centra*l (Bouchot et al. 2005).

Subalkaline or alkaline granitic intrusions are associated with pegmatitic, greisen, vein type and skarn deposits. Sn, W, U, Fe, Be deposits containing also Cu-As or Au-Bi-Te minerals, and polymetallic lodes occur at several sites in the Massif Central, in Brittany (France), and in Cornwall, *Cornubian Ore Field* (Scrivener 2006). At *Cínovec* and *Altenberg* greisen-type Sn-Li-W deposits were mined, also occurring in the NW part of the Massif Central (*Beauvoir*). Late-stage alkaline intrusions produced REE-enriched pegmatites in the Bohemian Massiv (Goodenough et al. 2016).

The post-orogenic Central European Basin System was filled by the Zechstein Sea in the Permian era. Several salt deposits were formed here. The succession also contains a thin (0.3–4 m), but continuous and regionally developed bituminous marl horizon enriched mainly in base metals: this is the *Kupferschiefer,* named after mined outcrops in Germany, extending from Silesia in the East to the North Sea in the west. The main ore minerals are Cu, Pb and Zn sulphides, but further enriched elements of some deposits include V, Mo, U, Ag, As, Sb, Hg, Bi, Se, Cd, Tl, Au, Re and PGE. Prospective and mining areas were summarised by Zientek et al. 2015. Large underground mines and reserves are in Poland (*Lubin*, *Polkowice-Sieroszowice* and *Rudna).* Post-orogenic Permo-Mesozoic sedimentary sequences host several other deposits beyond Kupferschiefer-related ones. In Silesia, the Polish Basin contains MVT Pb-Zn-Ag deposits (e.g. *Olkusz*) with 30 Mt estimated reserves in Triassic carbonates (Coppola et al. 2009).

8.5 Alpine Europe

8.5.1 Pyrenees and Betic Cordillera

Alpine processes produced no noteworthy ore deposits in the Pyrenees and in the Betic Cordillera, except some Pb-Zn mineralisations (also containing silver). In the Central Pyrenees sediment-hosted Zn-Pb-F-Ba deposits occur at *Pierrefitte Les Argentiéres* (Munoz et al. 2016). Shelf-margin facies limestone and dolomite of the Basque-Cantabrian Basin in the North Pyrenean Belt hosts several Pb-Zn deposits of sedex, stratabound or vein types; *Reocín* is the largest one among these (Águeda Villar & Salvador González 2009).

In the Betic Cordillera three groups of polymetallic ores are present (Arribas & Tosdal 1994): carbonate-hosted stratabound F-Pb-Zn-Ba; hydrothermal vein-type deposits of Pb, Zn, Fe and Ag and epithermal veins of Pb-Zn-Ag-Cu-Au and Au-Cu-Te-Sn. PGM-enriched chromitite deposit occurs in the Ojen lherzolite block (Torres-Ruiz et al. 1996).

8.5.2 Alps

Though the countries of this region are no large metal producers, ore mining in the Alps is still an important activity and possibility, mainly in the eastern part. This region lacks Cenozoic volcanism and related deposits. Data are summarised with a metallogenic map by the Geological Survey of Austria.

There are several Pre-Alpine deposits in this region, sometimes with Alpine metamorphic overprint. VMS Fe-Cu-Zn, stratiform Au and stockwork W-Sb-Hg deposits were produced by Palaeozoic magmatic-hydrothermal processes, now hosted by metamorphic rocks. The W-mineralisation (also enriched in Sn, U and F) at *Mittersill* in the tectonic window of the High Tauern, hosted in gneiss, is a world-class deposit. Polymetallic veins, Li pegmatites, disseminated Au and U(-Cu) are also known. Fe-Ni-Cu sulphides with PGE enrichment occur in the mafic rocks of the suture zone. Lens-shaped magnetite and chromite deposits of the *Aosta Valley* are hosted by ultramafic rocks. The 'Grauwackenzone' is known for several polymetallic (Cu, Fe, Ni, Co, Hg) sulphide deposits. Sedex Pb-Zn-Ag deposits are characteristic in the *Graz Palaeozoic Complex* (Weber ed. 1997).

In the Eastern Alps, significant stratiform and stratabound ore deposits are hosted by the Permian–Jurassic sedimentary successions. 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). At *Idrija* (Slovenia), Carboniferous-Triassic sedimentary succession hosts world-class epithermal Hg deposits, but mining is abandoned by now (Palinkaš et al. 2008).

In the Southern Alps, Triassic alkaline magmatism produced skarn type magnetite, W-Mo-Sn-Bi and polymetallic sulphide deposits related to granite intrusions (*Trento, Traversella, Brosso* in Italy) (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). Au- and Sb-enriched quartz veins, mesothermal gold lodes (e.g. the '*Tauerngold*', or the *Monte Rosa Gold District*) are considered as postorogenic deposits (POHL & BELOCKY 1999) *(Figure 43).*

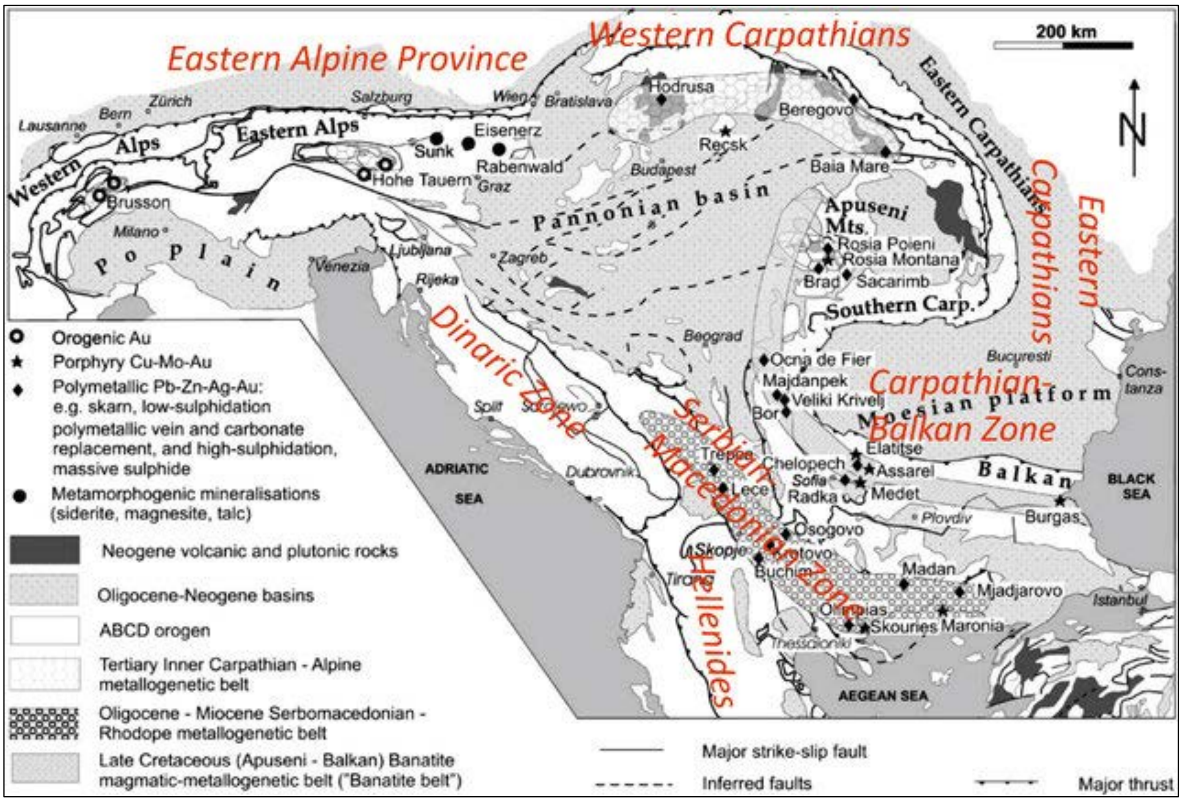


Figure 43: Metallogenic provinces within the Alpine-Balkan-Carpathian-Dinaride region, indicating the position of important mineral deposits. Source: Melcher & Reichl, 2017

8.5.3 Apennines

The region has an ancient tradition of mining, but ore mining activity decreased to the start of the 21st century and ceased recently. The significant ore deposits of the Apennines are concentrated to the northern region, and these relate to Cenozoic magmatism.

The Apennine Peninsula and attached islands contain several deposits inherited from Pre-Alpine processes like the previous regions. Lower Palaeozoic rocks of *Sardinia* and *Corsica* host MVT and SEDEX Pb-Zn ore deposits with stratabound Sb-Hg-W-As ores, also non-sulphide zinc deposits (Mederer & Chelle-Michou 2011). VMS deposits and vein type Fe-Cu-Ni-Zn-Pb-sulphide mineralisation with Au enrichment are common. PGE-bearing chromitites occur in Mesozoic ophiolite complexes of the Northern Apennines (e.g. Cu ores of *Elba*) (Zaccarini & Garuti 2008).

The Oligocene-Miocene-Quaternary volcanism produced several epithermal deposits of Sb, Hg, Au and Ag in Tuscany (e.g. *Cetine Sb*), on Elba (e.g. *Procchio* Sb), on Corsica and on Sardinia (e.g. *Furtei* Au). Au occurs in quartz vein- and carbonate-hosted (Carlin-type) deposits. Some geochemical characteristics indicate remobilisation of mineralisations from the Pre-Cenozoic basement (Lattanzi 1999). In the 'Colline Metallifere' district and on Corsica base metal deposits are also important. The *Mt. Amiata* mining district comprises of world-class Hg deposits, and replacement ores in carbonates under impermeable overlying strata, related to recent geothermal systems. Significant Hg emission is an unwanted by-product of geothermal power plants (Rimondi et al. 2015).

8.5.4 Carpathians

The arc-shaped Carpathian Mts. and the Pannonian Basin inside this arc host several significant deposits with rich mining traditions *(Figure 43)*. Cenozoic calc-alkaline volcanism is widespread: the Late Cretaceous–Paleocene 'banatites' in the Southern Carpathians, continued also in the Balkan Range, and the Oligocene–Miocene suite in the Western Carpathians (Slovakia and Hungary), in the Eastern Carpathians and in the Apuseni Mts. (Romania). All of these are dominantly andesitic, but dacites and, mainly from the Miocene, rhyolites are also voluminous. Several major porphyry, skarn and epithermal base and precious metal deposits are attached to these volcanic complexes, and ore mining is still active, ranking the Carpathians one of the world's major base metal reserves. Pre-Cenozoic sequences host several inherited Variscan deposits, affected by Alpine metamorphism, and Alpine deposits.

In the Eastern Carpathians, MVT (*Blazna-Guset* area), and VMS deposits (e.g. *Baia Borsa*) occur in the Rodna and Maramures Mts and the Rebra Paleozoic. Kuroko-type VMS deposit occurs at *Tulghes*. Rhyolitic volcanism-related base metal sulphide veins (e.g. *Muncelul Mic*) are typical in the Poiana Rusca Mts. in the southern areas (Kräutner 1996). The Mesozoic Ditrău alkaline complex hosts REE, Nb and Mo bearing lodes at *Jolotca* (Honour et al. 2018). In the Făgăraş Mts., carbonate-hosted stratiform Pb-Zn, magmatic-associated Ni-Cu-Co, polymetallic vein-type Pb-Zn-Cu-Au-Ag, graphite and Au mineralisation occur in the metamorphic sequences. Post-metamorphic sulphide deposits, occasionally with Au mineralisation are controlled by major faults (Milu 2010).

In the Western Carpathians, stratiform and stratabound (metasomatic), often black shale-hosted and vein type siderite, barite, manganese and base metal sulphide mineralisations are the most abundant in the Slovakian Ore Mountains (e.g. *Nižná Slaná* for metasomatic, *Rudňany* for vein type). Vein minerals are of Mesozoic age in several cases. Such paragenesis is also present in metasomatised Triassic carbonates in NE Hungary (*Rudabánya*). Stratiform Mn mineralisations occur in several localities hosted by Jurassic and Oligocene black shales. The *Úrkút* Mn deposit (Hungary) is enriched in REE (GRASSELLY & PANTÓ 1988). Stratiform W occurs at *Kokava nad Rimavicou*, stratabound and vein type Sb-As-Au in the Malé Karpaty Mts. (e.g. *Pezinok*) (GRECULA et al. 1996). Major karst bauxite deposits were mined in the *Bakony Mts*, Hungary.

Variscan granite intrusions contain pegmatites with HFSE mineralisation. Granite bodies of the Western Carpathians are associated with Sn-W-Mo (e.g. *Hnilec*) and U-REE-Au lodes. U-Mo-Cu and magnetite deposits (e.g. *Kokava nad Rimavicou*) of the Slovakian Ore Mts, Sb-Au (e.g. *Dúbrava*) and W-Au (e.g. *Jasenie-Kyslá*) deposits in the Low Tatra Mts. are further important mineralisations in the Western Carpathian region (GRECULA et al. 1996).

Large volcanic complexes comprise several subvolcanic intrusive bodies and extensive rock alterations also affecting country rocks, producing porphyry, stockwork, vein type and metasomatic (skarn) deposit complexes. Most large deposits of the Late Cretaceous–Paleocene 'banatite' region are in the Balkan area (see section Balkan Peninsula and Aegean area). The *Moldova Noua* porphyry Cu-Mo deposit in the Banat Mts. and the skarn deposits of the Apuseni Mts. (e.g. *Baisoara, Baita Bihor*) can be mentioned here as important ones (Quadt et al. 2005).

Several minor volcanic bodies and attached polymetallic sulphide mineralisations were produced by the Late Paleogene volcanism along the Mid-Hungarian Mobile Belt, 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 most important deposits are in the Štiavnické Mts, Slovakia (a traditional precious metal mining district with the centres at *Banská Štiavnica, Kremnica and Hodruša*) and in the Gutin Mts, Romania (*Baia Mare, Baia Sprie, Cavnic*). However, most volcanic edifices host at least vein type meso-epithermal deposits, e.g. *Pátka* base metal+fluoride veins (Velence Mts), *Gyöngyösoroszi* base metal veins (Mátra Mts), *Telkibánya* Au-Ag veins (Tokaj Mts) in Hungary; and *Klokoč* porphyry Au (Javorie Mts) in Slovakia.

A separate, but even more important area of this volcanic period is the ore district '*golden quadrangle*' in the Metaliferi Mts (part of the Apuseni Mts.) with deposits like the *Roşia Montana* epithermal Au-Ag, *Roşia Poieni* and *Bucium-Tarnita*. Unexploited Au reserves still are estimated to exceed 1000 t (Popescu & Neacşu 2012).

8.5.5 Balkan Peninsula and Aegean area

This area is the southeastern continuation of the Alps and the Carpathians, partly with overlapping metallogenic regions. Like in the Carpathians, ore mining is a current issue with several large deposit groups attached to Cenozoic volcanic structures or to Mesozoic ophiolite complexes *(Figure 44).*

Most of the Pre-Cenozoic deposits are located in the Dinarides, in a lesser extent in the Palaeozoic formations of the Balkan Mts. These are stratabound Pb-Zn deposits in the Velebit Mts. (*Gračac*), SEDEX Fe-Mn in the Medvednica Mts., and magnetite at *Ključ*. Meso-epithermal polymetallic veins occur at several sites in the Sava and the Durmitor nappes (e.g. *Litija*). HS and LS epithermal deposits of the Mid-Bosnian Schist Mts. were exploited for the Roman Empire (Palinkaš et al. 2008).

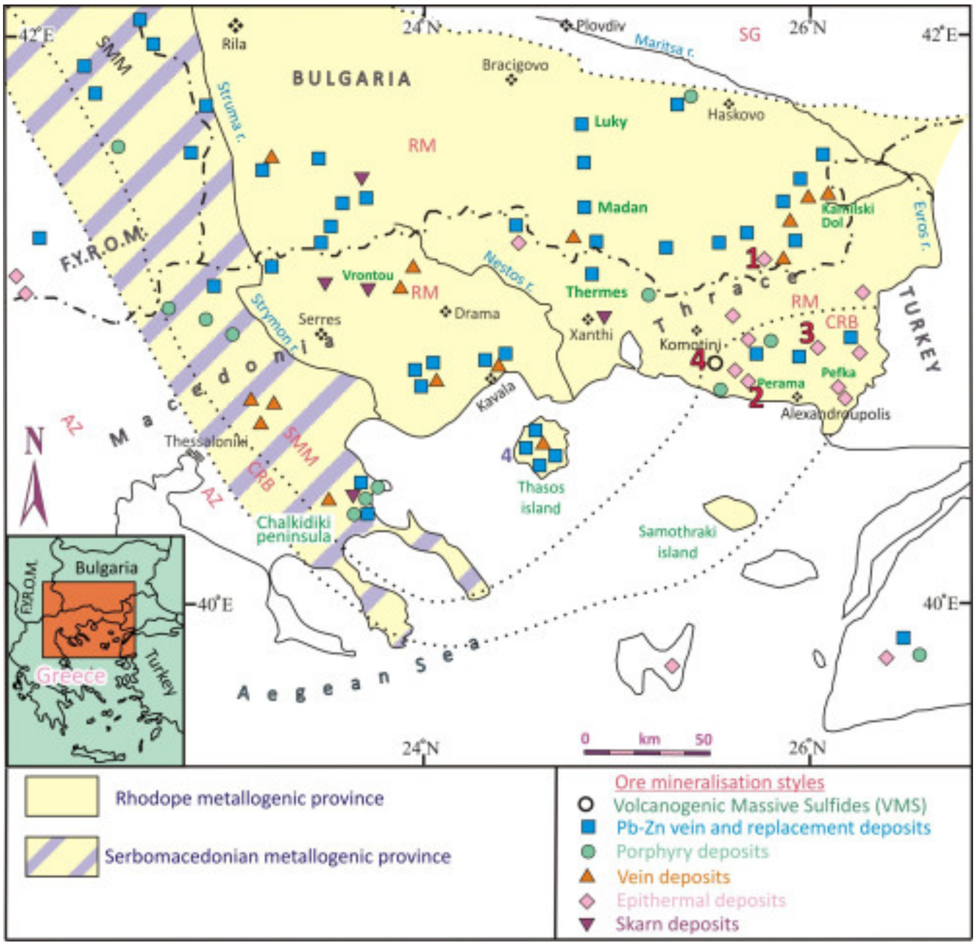


Figure 44: Simplified map displaying the distribution of the ore deposits within the Rhodope and the Serbomacedonian metallogenic provinces in the southern Balkan Peninsula. RM: Rhodope Massif, SMM: Serbomacedonian Massif, CRB: Circum Rhodope Belt, AZ: Axios (Vardar). Source: https://authseg.wordpress.com/2016/12/18/293/

The West Balkan Mts. contain Pb (*Chiprovtzi*), Au-sulphide (*Govezhda*) and polymetallic (*Iskar-Vratsa*) ores, exploited mainly for silver (Christova et al. 2003). Carlin type disseminated Au occurs at *Bakovići*; Permian Kupferschiefer-like Cu at *Škofje*. Pegmatites and sediment hosted U can be found in the Slavonian Mts. (Palinkaš et al. 2008).

Related to the Triassic intracontinental magmatism, VMS Cu-Pb-Zn deposits (e.g. in the *Strandja* and *Gramatikovo* ore districts) and stratiform Fe (*Kremikovtsi,* Balkan Mts) developed. Triassic carbonates of the Moesian Platform host MVT Pb-Zn deposits (Palinkaš et al. 2016). Carbonate hosted SEDEX Fe and Pb-Zn (e.g. *Vareš, Veovača*) occur in Central Bosnia.

Basic and ultrabasic magmatites produced significant PGE bearing Cr and Ni deposits in the region. The Jurassic Vardar Ophiolite Complex hosts widespread podiform chromite (*Ozren* and *Borja Mt.*) (Palinkaš et al. 2008). PGE bearing chromite deposits are also present in the ophiolitic complexes elsewhere like *Veria* in Greece or *Bulqiza* in Albania (Haldar 2017).

Ni laterites developed on the ophiolitic rocks in the Lower Cretaceous. The Cretaceous collisional setting of the Pirin-Rhodope zone produced granite intrusions also with attached Ni-Fe-Co-Cr laterites and oolitic Fe deposits (Popov 2002). Ni laterites of Greece and Albania are registered as significant reserves. Bauxite is also widespread in the region, both from Mesozoic and Cenozoic eras, with Greece as the biggest producer in Europe. REE enrichment of the bauxite may also be an important resource.

The Apuseni-Banat-Timok-Srednogorie zone is the continuation of the Banatitic Magmatic and Metallogenetic Belt from the Carpathians. It contains major porphyry copper (±Au and Mo) (e.g. *Majdanpek, Assarel, Elatsite*) and massive sulphide (Cu, ±Au) (e.g. *Bor, Chelopech*) deposits, associated with minor polymetallic skarn and sediment-hosted Au deposits (Popov 2002).

Hydrothermal Cu-Au and Pb-Zn-Au veins are typical in the *Srednogorie*. The Rhodope Massif (with potassic volcanics) exposes vein and replacement Pb-Zn-Ag deposits hosted by metamorphic rocks (e.g. *Madan*), low grade porphyry Cu-Mo with epithermal polymetallic ores, and sediment- and breccia-hosted Au (e.g. *Ada Tepe* in Bulgaria, *Alshar* in Macedonia, *Perama Hill* and *Sapes* in Thrace). Sb is hosted by LS epithermal veins (e.g. *Kallyntirion*) (Melfos & Voudouris 2012).

The Neogene volcanism of the Trans-Balkan belt produced further vein-type or metasomatic Pb-Zn-Ag(-Au) and Au(-Ag-Te) deposits (mainly in the *Chalkidiki* and *Kilkis* regions with active mines). In the Aegean Sea, the volcanism from Late Oligocene to recent time 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.* The epithermal polymetallic and Au deposits of *Milos* Island are significant (Alfieris et al. 2013).

9 CONCLUSIONS

The aim of this study is to provide an ore geological background for the application of the robominers technology, summarise the potential geological situations, and define key input parameters for the engineering design of the system components. Based on literature data, the different ore deposit types are listed and characterised, and the relevant features are discussed so that the potential targets of the technology can be selected.

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. Special emphasis was put on those deposit types which can be relevant for the development of the robominers technology: magmatic, magmatic-hydrothermal and hydrothermal deposits, but in order to be complete, deposits of sedimentary origin are also described. Several geological cross sections support the visualisation of the deposits' features.

As the geometry of a deposit is a basic determining factor for mine planning, the shapes and dimensions of the ore bodies are discussed in a separate chapter. Two-dimensional deposits, e.g. veins or layered-type ores are of high importance. Three-dimensional deposits are generally subjects to conventional mining, but in the case of highly irregular deposits, the use of ore-following algorithm by the robominer and selective mining could increase the economy of exploitation.

Based on their geometry and other characteristics like rock mechanical features and economics, the ore deposits have been arranged in a ranking order by their suitability for robominers. The main targets are the stratiform sediment-hosted copper (SSC, Kupferschiefer-type) and the hydrothermal vein-type deposits, but VMS-type and lense-like or layered orthomagmatic deposits can also be of high importance.

The applicability of the technology was examined from different aspects like market, geotechnical, and operational conditions. The general technological requirements the robot should meet, for a wide range of deposit types, are listed in Section 6.3. The most important requirements are the capabilities for directional drilling and the real-time chemical and mineralogical analysis. In the surface control room, algorithms for following the ore, designing the mine layout and the scheduling the extraction should be developed.

Three possible geological and mining scenarios have been outlined in the study, with the detailed characterisation of a specific ore deposit example for each scenario. The described scenarios are (1) operating and abandoned mines with known remaining unfeasible resources (Neves-Corvo), (2) ultra-depth (Kupferschiefer, Fore-Sudetic Monocline), and (3) small deposits uneconomic for traditional mining (United Downs, Cornwall). The parameters of these scenarios are different from that of the traditional mining in several aspects.

In the last chapter, the four main metallogenic belts of Europe have been reviewed, and several potential target sites are mentioned and arranged according to these belts. The main conclusion is that options suitable for robominers can be found in any tectonic/metallogenic province. Numerous literature references may help the more detailed characterisation of a site if it is selected for the robominers application.

Outcomes from this deliverable serve as an input for ongoing and later work phases like simulations, virtual prototyping, design of the selective mining perception and production tools, development of the mining robot, and system integration.

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