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FORECASTING AND ASSESSING EUROPE'S
STRATEGIC RAW MATERIALS NEEDS

WP7 Historic Mine Sites revisited

Case Study

Historic mines in the Romanian Banat - With a special focus on the Ocna de Fier deposit

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Magnetite from Ocna de Fier. The width of the picture is 5 cm (from Popescu et al., 2013)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 731166





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1 Introduction

In the Romanian Carpathians, the main ore deposits are connected with the Alpine/Mesozoic to Tertiary-Quaternary magmatism. Archaeological evidence and historical manuscripts indicate that they have been mined since Roman and even pre-Roman times (e.g. Kissling 1967). They were described since the mid-XIXth century when von Cotta introduced the generic term of "banatite". The Cu(Fe) skarn deposits from Dognecea – Ocna de Fier (Banat Mountains) have been mined almost continuously since the Calcolithic period (1900–1700 BC) to the present (Nicolescu 1996). The skarns from Rézbánya (now Băița Bihor, Apuseni Mts.) and Banat were described and mapped by Karl F. Peters (1861). In 1864 Bernhard von Cotta published his classical study about Moravitz (Ocna de Fier), and other deposits he visited in Banat at Moldova Nouă ("Ujmoldova"), Sasca Montană ("Szaskabanya"), Ciclova ("Csiklova"), Oravița ("Oravitza") which are described as generated at the contact between younger intrusive rocks and Mesozoic limestones. He recognized that in all the contact type deposits from Banat, the intrusive, although highly variable petrographically, is consanguine. He proposes the name "banatite" for these rocks, mentioning that he does not intend to introduce a new rock type, but wants to underline the "banatite" consanguinity. As it becomes obvious from the original writing by von Cotta, the name "banatites" reflects their locus typicus (Banat region), covering parts of the south-western Romania and north-eastern Serbia. The term "banatites" has been preserved and extensively used, mostly defining a petrological province, rather than for depicting a rock typology (e.g. Codarcea 1931; Giușcă et al. 1965, 1966; Cioflica & Vlad 1973, 1977; Giușcă 1974; Rădulescu & Dimitrescu 1982; Ștefan et al. 1985, etc.). Other authors preferred time-related terms such as "Laramian" (Cioflica & Vlad 1973, 1977), "Late Cretaceous" or "Late Cretaceous - Early Tertiary" magmatites (e.g. Bocaletti et al. 1978; Cioflica et al. 1997; Downes et al., 1995), or involved a geographic, geotectonic and metallogenic significance: "Banat-Srednogorie belt" or "rift" (Popov 1981, 1987), "Banatitic Magmatic and Metallogenic Belt - BMMB" (Berza et al. 1998) or "Apuseni-Banat-Timok-Srednogorie Belt - ABTS" (Popov et al. 2000, Gallhofer et al. 2015).

Codarcea (1931) confirmed von Cotta's theory that all intrusive rocks in the Banat area are consanguine and agreed with the generic term "banatite" for them, and published the geologic map of the region (scale 1:25 000).

Most metallic ore deposits in the Southern Carpathians are part of the Banatite Magmatic and Metallogenic Belt (BMMB - Berza et al. 1998), a belt of Upper Cretaceous intrusives extending across SE Europe (Fig. 1). The belt extends over approximately 900 km in length and around 30 to 70 km in width. It occurs discontinuously from the Apuseni Mts. in the north, to the western part of the South Carpathians (Banat) in Romania, and further South to the Carpathians of East Serbia and still further East to Srednogorie (Bulgaria), reaching the Black Sea coast (Fig. 1). The



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Black Sea may be interpreted as an interruption of the south-east European outcrop of the BMMB, suggesting that an Asian segment might exist, embodied by the Late Cretaceous Eastern Pontide volcano-sedimentary belt and associated ore deposits of North Anatolia (Akinci 1984). The author mentioned the similarities with the south-east European magmatic and metallogenic coeval counterparts (see Ilinca et al. 2011).

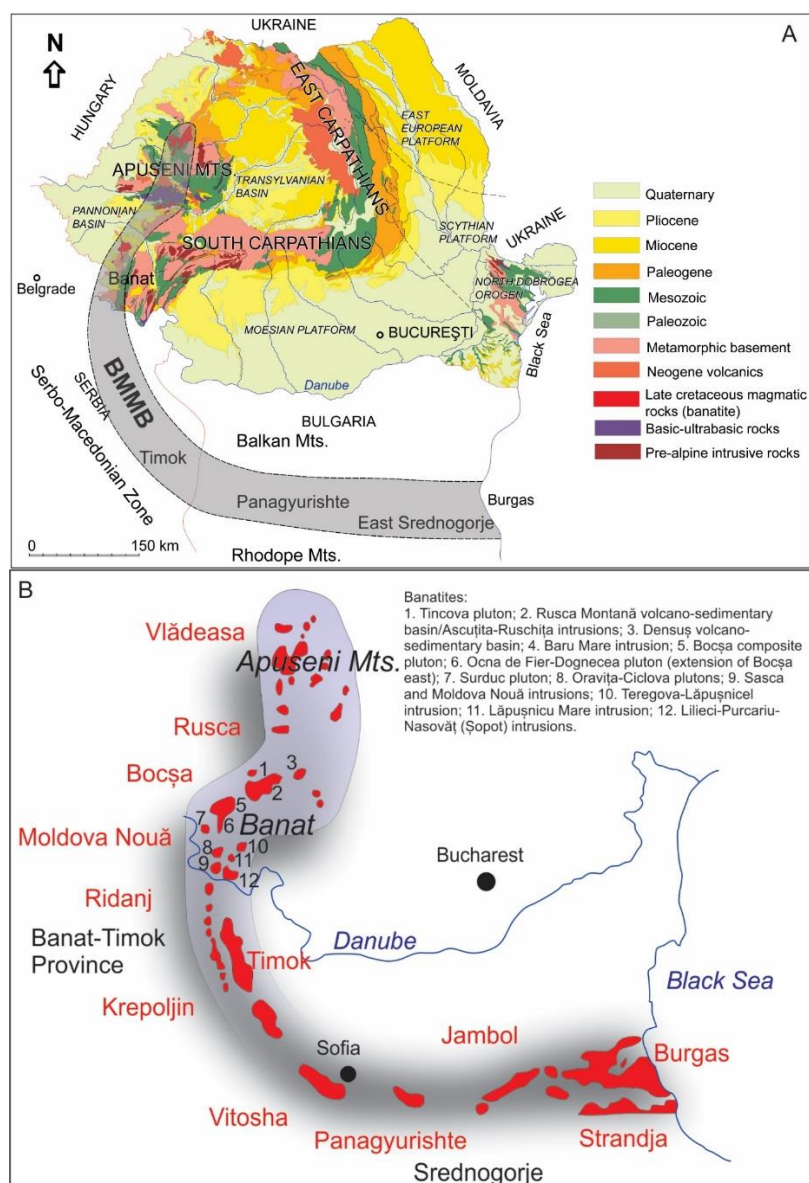


Figure 1: Geological sketch map of Romania (Geological Institute of Romania) and BMMB (Berza et al. 1998) location in South-East Europe. B) Detail of the BMMB extension over Romania, Eastern Serbia and Bulgaria (after Ilinca et al. 2011, Vlad 2020).

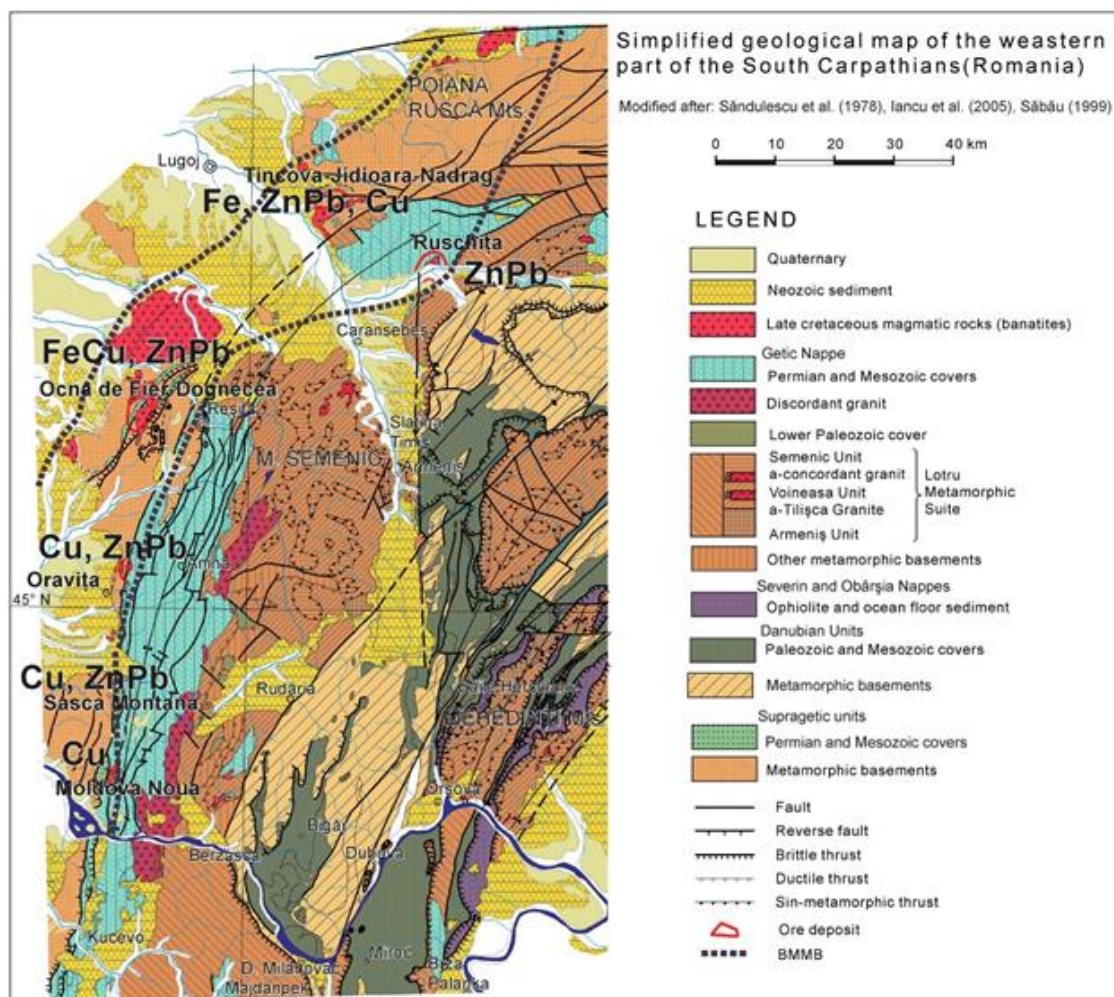


Figure 2: Simplified geological map of the western part of the South Carpathians (Romania) (modified after Săndulescu et al. 1978, Iancu et al. 2005, Săbău 1999) and the location of the main skarn deposits.

2 Geological background

The banatite intrusions in the South Carpathians Mts. (Fig. 2) crosscut the metamorphic basement of the Supragetic Nappes (Streckeisen 1934, Iancu 1982, 1984, 1985, 1986) and the Permian and Mesozoic sedimentary cover of the Getic Nappe (the Reșița-Moldova Nouă synclinorium). The (Lower) Supragetic Nappes (metamorphic Lower to Middle Paleozoic basement with sparse Mesozoic cover deposits) are (from west to east) the Bocșa Nappe and the Moniom Nappe; they overlap the Reșița Nappe and the Lupac-Dealul Vremii Unit, assigned to the Getic Nappe (Iancu 1982).



The Bocşa Nappe comprises the Bocşiţa Drimoxa Formation and the sedimentary cover (Jurassic-Lower Cretaceous limestone). The Bocşiţa - Drimoxa Formation consists mainly of garnet-bearing paragneisses with oligoclase porphyroblasts, and amphibolites overprinted by retrogression. It corresponds probably to a part of the Locva "Series" exposed at the entrance of the Danube into Romania (Săndulescu & Dimitrescu 2004). The Bocşiţa-Drimoxa Formation is overlain, west of Reşiţa, by limestones of Upper Jurassic-Lower Cretaceous age.

The Moniom Nappe (Iancu 1982) consists of the volcano-sedimentary Valea Satului Formation (Upper Devonian-Lower Carboniferous). It includes mainly mafic low-grade metatuffs (chlorite-actinolite-epidote-albite schists) with interlayered metapelitic and carbonatic rocks, acid metatuffs and small bodies of gabbro and diorite-granodiorite (Iancu 1982, Iancu & Mărunţiu 1994).

In Serbia, the highest structural unit corresponding to the Western Supraetec is the Morava Nappe. The main part of its basement consists of the "Vlasina Series" (Dimitrijević 1997). It is overlain at Bosilegrad, in south-eastern Serbia, by the anchimetamorphic Lisina beds, the Tremadocian age of which is constrained by Brachiopods. The Vlasina Series could be compared to the Locva "Series" or to the Bocşiţa-Drimoxa Formation (Săndulescu & Dimitrescu 2004).

2.1 Geochemistry of banatites (after Berza 1998, Ilinca et al. 2011, references therein)

The banatites define, in major and trace element variation diagrams, a calc-alkaline to high-potassium calc-alkaline trend ranging from 50 to 70% SiO₂. They are magnetite-bearing I-type granitoids enriched in LILE (large-ion lithophile elements)/LREE (light rare-earth elements) and depleted in Nb, Ta and Zr, common features for magmas associated with subduction zones. Initial Sr isotopic ratios (S_{ri}) vary from 0.7042 to 0.707 and εNd(t) values range from +3,9 to -3,7. Variations of S_{ri} and εNd(t) values with SiO₂ show minor crustal assimilation. The generally positive εNd(t) values, together with moderate S_{ri} indicate that parental magmas result from partial melting of a Rb-enriched and LREE-depleted source, most probably a young mafic lower crust derived from a heterogeneous lithospheric mantle. Selective Rb enrichment probably occurred during a previous subduction event by metasomatism of the overlying mantle wedge, either in the Early Cretaceous or earlier, as suggested by depleted-mantle model age (TDM).



2.2 Geodynamic setting (after Berza 1998, Ilinca et al. 2011, references therein)

Numerous models have been published in order to explain the formation and the geodynamic significance of the BMMB (reviewed in Berza et al. 1998, Ciobanu et al. 2002, Zimmermann et al. 2008, Ilinca et al. 2011, Ilinca 2014, references therein). The tectonic debate is focused on the role of subduction and extension in the overall collisional evolution of the Alpine–Carpathian orogen during Late Cretaceous-Tertiary time:

- subduction of oceanic crust: e.g. Rădulescu & Săndulescu 1973, Rădulescu et al. 1993 (westward subduction of Mureș & Severin oceans); Savu 1987, 1993 (north-west directed subduction of the Severin ocean); Boccaletti et al. 1974, Zimmermann et al. 2008 (north-east directed subduction of the Vardar ocean lithospheric slab); Schmid et al. 2008; Gallhofer et al. 2015;
- rifting - e.g. Antonijević et al. 1974; Popov 1981, 1987, 1995;
- post-collisional extensional regime – e.g. Berza et al. (1998), Berza (1999), Nicolescu et al. (1999), Popov et al. (2000), Neubauer (2002) (orogenic collapse affecting the upper crust, mantle delamination due to slab break-off in the Late Cretaceous following the Jurassic and Lower Cretaceous northwards directed Vardar-Axios ocean subduction);

Based on the paleomagnetic data from the Carpathian and Pannonian areas, Panaiotu et al. (2005) suggested a two-step rotation model, to explain the up to 90° declinations measured on banatites in the Apuseni Mountains and in the Southern Carpathians. The Late Cretaceous paleoaltitude calculated for banatites by Panaiotu et al. (2005) is $24^{\circ}\text{N} \pm 4^{\circ}$. At the time of their emplacement, the banatites of the BMMB had an east-west spatial trend, and continued to the east with the alignments of the Western and Eastern Pontides.

2.3 Skarn deposits

Skarn ore is the most frequent type of mineralization along the BMMB. The most important historic skarn deposits belonging to the BMMB on the Romanian territory are FeCu(ZnPb) Ocna de Fier - Dognecea skarn deposit in the north, Cu(Mo, W, Bi) Oravița, Cu(Mo) Sasca Montană, and Cu Moldova Nouă skarn and porphyry deposit in the south (Fig. 2, Tab. 1). Nicolescu (2005) presented an inventory of other small skarn occurrences within the BMMB (subeconomic) in western Romania, such as CuMo Liliaci - Liubcova (Southern Banat), CuMo Tincova (Poiana Ruscă Mts.), Fe(ZnPb) Ruschița (Poiana Ruscă Mts.), high-temperature calcic skarn Măgureaua Vaței (Cornet Hill and Cerboia Valley, Apuseni Mts.) (Pascal et al., 2001 and references therein; Săbău & Negulescu 2019), and Budureasa and Valea Leșului skarns (Apuseni Mts.).



3 Historic mine sites

During the communist regime in Romania, all known old mines were re-investigated and some of these (or their waste dumps) were mined again in 1970s-1980s, even at low contents of the main commodities (Cu, Fe, Zn, Pb, Au, Mn). Therefore, the historic mines in Romania commonly were closed in 1990s-2000s. In 2006, a country-wide mine closure program has begun, which included tens of mines from Romania. In the present, only 11 mines of metallic ore are under license of either mining or exploration and, based on this, they were not considered historic mines in this study. Among the closed mines in Banat we consider as historic mines only those whose mining has begun before 1900, i.e. Ocna de Fier, Dognecea, Oravița-Ciclova, Sasca Montană and Moldova Nouă (the skarn mineralisation). Systematic mining (with underground mines dug with the chisel and hammer) was done in Banat by the Romans. In 123 A.D., Tacitus named the mining region of Banat “centum putei”, meaning one hundred pits (Tăutu, 2009), which is also the name of a Roman fort whose remnants are preserved in the region. A document issued in 1437 by the ruler of Banat mentioned active mining at Sasca, Ciclova and Oravița (Tăutu, 2009). In the interval 1824-1854, the average annual production of non-ferrous metals resulted from the ore of these mining fields was: 282 t Cu, 36 t Pb, 42 t Zn, 366 kg Ag and 3.5 kg Au; the production of non-ferrous metals decreased gradually after 1870 (Tăutu, 2009), with a new peak of extraction in the 1970s and 1980s.

3.1 Ocna de Fier - Dognecea

The Fe-Cu skarn deposit at Ocna de Fier - Dognecea is the largest skarn deposit in the Banat Region (Dognecei Mts., Caraș-Severin county) (Fig. 2). The orefield contains more than 30 irregularly shaped orebodies placed within a narrow NNE-SSW zone (10 km) between Ocna de Fier and Dognecea villages, within the contact aureole of granodiorite intrusions (Fig. 3), on both flanks of a N-S trending body of Jurassic-Lower Cretaceous limestone and the schists of the Bocșița-Drimoxa Formation (Fig. 3). The orebodies have vertical extension between 200 and 350 m, ending at the base of the limestone at the contact with the crystalline schists (e.g. Nicolescu 1996, Ciobanu & Cook 2004). The exoskarn deposit is approximately 50 m thick and yielded 15 million tons of Fe-dominated ore before exploitation ceased in 1993 (13 Mt for Ocna de Fier and 2 Mt Dognecea). The ore grade was 30-35% Fe, 0.5% Cu and minor grade Zn-Pb at Ocna de Fier and 3.69 Zn, 1.92 Pb and minor grades Cu, Ag at Dognecea (Cook & Ciobanu 2001, Ciobanu & Cook 2004) (Tab.1).

The big ore reserves, the unusual (for middle 19th century) genetic type, as well as the rich mineral parageneses (more than 110 valid mineral species), led to major scientific interest of



the geologic community in the Ocna de Fier-Dognecea deposit. This is reflected by a large number of geological reports and scientific papers published on subjects related to the area.

3.1.1 Mining history in the Ocna de Fier – Dognecea area

A detailed mining history of the Ocna de Fier - Dognecea district was presented by Nicolescu (1996). The area is well known due to the iron deposits almost continuously exploited for about 4000 years, with archaeological evidence attesting to the Bronze Age (1900 - 1700 BC) as the beginning of mining activities in the region (Kissling 1967). At that time, mining consisted of collecting native copper found in the oxidation areas of ore bodies. Subsequently, due to the presence of iron mineralizations on the surface, it gradually switched from bronze metallurgy to the superior technique of iron metallurgy.

The Romans paid special attention to the ores of Dacia (approximately the present-day Romania). In the literature, there are mentioned the Roman galleries for gold, such as from Golden Hill (Romanian Cracul de Aur) on the territory of Ocna de Fier (Kissling, 1967). The extraction of gold from the Golden Hill took place until the 13th century. Gold was also extracted in the Iuliana quarry area (Fig. 3).

Mining in the area continued during the Turkish occupation (1554 - 1716) through the continuous extraction of copper, lead, zinc, silver and iron ores. After the Turkish - Austrian peace treaty at Passarowitz (1718), the Banat region became part of the Habsburg Empire. It was a period of mining boost, in which Bocşa and Dognecea became important metallurgical centers, focusing in iron and copper metallurgy. In 1717, "Banat Commission for Mining Organisation" (Banater Bergwerkseinrichtungskommission) was established, with the headquarters in Timișoara (Tăutu, 2009). After 1740, the extraction of Pb, Zn, Ag and Au joined the expansion of Fe and Cu mines. At Cracul de Aur hundreds of meters of adit were made in search for gold, but apparently the exploitation of gold was not profitable, although the literature mentions contents of 6.25 g/t Au and 5.38 g/t Ag. At Ocna de Fier, the mining activity was carried out both in open pits and underground, while at Dognecea underground mining prevailed. In 1764, Dognecea produced 196 t Cu and 14 kg Ag, while in 1770 produced 143 t Cu (Tăutu, 2009).

During the 18th and 19th centuries, iron production increased continuously (150 tons in 1897 - Kissling, 1967). This increase, combined with the discovery of important coal deposits some 20 km south-east of the area, triggered the development of an important iron smelting centre at Reșița. A USGS report on the iron resources of Europe (Roessler, 1921) mentions pre-World War I productions of ca. 175,000 t/year and known resources of 1 Mt, probable resources of 3 Mt and possible resources of 4 Mt (all as metallic iron). However, after the First World War,

Waste dumps

Fluvial deposits

Alluvial Fe deposits

Tertiary sediments

Ocnă de Fier-Dognecea intrusion (granodiorite)

Smaller intrusive bodies

Skarn

Moniom Nappe

Epidote-chlorite amphibole schist

Bocșa Nappe

Sedimentary cover

Jurassic-Lower Cretaceous limestone

Bocșita-Drimoxa Formation

micaceous gneiss

mica schist

banded gneiss

adit

shaft

quarry

geological limit

Tertiary limit

thrust

contact halo

Colțan

Ferendia

Moravița

Ogășul Groza Mare

Ogășul Izvorul Negru

Ogășul Dealovăi

Ignățiu & Franciscus Paulus

Ocnă de Fier

Terezia endokarns

Magnet

Elias Simon Iuda

Iuhana

Ocnă Turcescă

Ștefania

Nicolae

Terezia Hill

Valca Arieș

Simu

Iudea

Dognes

Ensoarnea

0 5 km

N

The main mining works were (from north-east to south-west) (Fig. 3, 4): Paulus, Franciscus, Ignatius, Terezia, Jupiter, Magnet, Petru & Pavel, Simon Iuda, Elias, Iuliana, Ocna Turcească, Aurora, Ferdinand. Their features are summarized in Table 1.

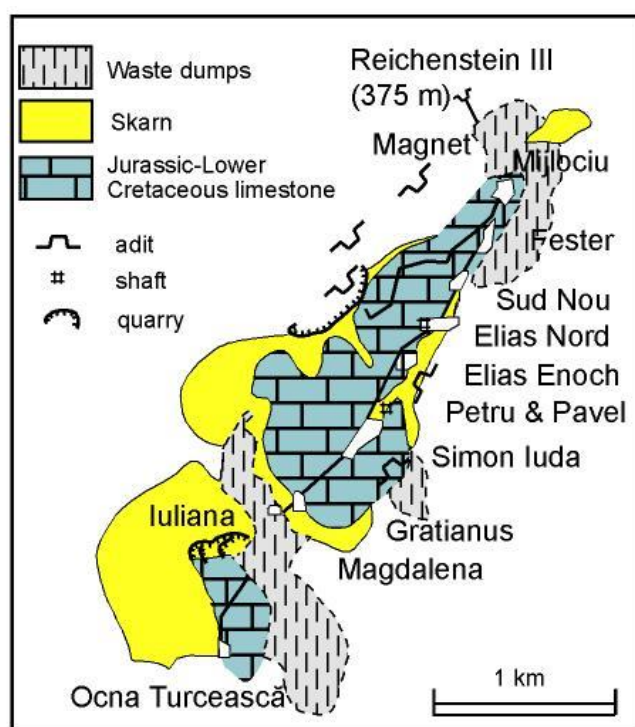


Figure 4: The orebodies from Ocna de Fier-Dognecea District projected at surface within the central part of the ore field (detail from Fig. 3, after Cook & Ciobanu 2001).

Currently, the reserves of magnetite, lead, zinc and copper that made the region famous in the past are depleted. The mining activity in the Dognecea area ended in 1989 and in Ocna de Fier in 1993. Only two quarries from which marble is extracted are currently functional in the area. However, Nicolescu (1996) mentioned about 2 Mt of hematite skarns left in the deposit. With appropriate technology for the extraction of iron ore associated with the exploitation of important reserves of industrial minerals (e.g. garnet) and marble/granodiorite, the region could again become of economic interest.

3.1.2 Geological background of the Ocna de Fier-Dognecea area

A comprehensive description of the geological setting of Ocna de Fier and its southern extension, Dognecea, is presented by Nicolescu (1996), Berza (1998), Ciobanu (1999), Ilinca et al. (2011), and others.

The basement of the Ocna de Fier - Dognecea area is mainly represented by the metapelites (albite-muscovite-chlorite gneiss, subordinate microcline-bearing lenticular augen gneiss,



muscovite $\pm$ feldspar-bearing quartzite and chlorite-mica schist) of the Bocşa Nappe of the "Supragetic" unit (Streckeisen 1934, Iancu 1982-1986) (Fig. 3, 4). A narrow, NNE - SSW trending Upper Jurassic-Lower Cretaceous limestone syncline lies discordantly over the metapelites. Metapelites and limestones are intruded by a suite of calc-alkaline igneous rocks, mainly of granodioritic composition (banatites) that gave contact phenomena forming, through contact metamorphism and metasomatism, hornfels, skarn or marble, depending on the lithology of the affected rocks. Iancu (1984) estimated the age of the metapelites as Upper Proterozoic metamorphosed under almandine amphibolite-facies conditions; during the Early Caledonian the metapelites were retrograded to greenschist-facies parageneses. However, the estimated age is questioned by Ar/Ar data (Dallmeyer et al. 1996) that give a Late Variscan age (302 - 317 Ma) for the latest greenschist facies thermometamorphic event of the Supra-Getic Unit occurring 200 km eastward, in the Făgăraş Mountains (see Nicolescu et al. 1999).

A compilation of radiometric dating for banatites was published by Ciobanu et al. (2002), pointing to age spans between 49.5 - 77 Ma in Apuseni Mountains, 47.2 - 110 Ma in Poiana Ruscă Mountains, 67 - 89 Ma in Banat, 38 - 93 Ma in Serbia and 67 - 94 Ma in Bulgaria, respectively. Maximum of age frequencies occur in the 65-95 Ma interval (Turonian–Maastrichtian), a shorter time span, confirmed by recent U-Pb dating (Gallhofer et al. 2015).

Geothermobarometry on hornfelses indicates a peak temperature of 600°C at a depth of cca 8 km (2.8 kbar) at the time of intrusion (Nicolescu & Cornell 1996).

3.1.3 Inventory of the skarn minerals (Tab.1)

The mineralogy and composition of major minerals at the Ocna de Fier and Dognecea deposits are presented by Kissling (1967) and Vlad (1974). A large number of studies were subsequently published related to banatites and ore deposits mineralogy, using modern microanalytical methods, to confirm mineral species and to integrate the data in a comprehensive genetic model (Ilinca 1998, Nicolescu 1998, Nicolescu & Cornell 1999, Nicolescu et al. 1999, Marincea 1999, Ciobanu 1999, Ciobanu & Cook 2000, 2004, Ciobanu et al. 2002, Cook & Ciobanu 2001). About 113 valid minerals and two type locality minerals (<https://www.mindat.org/>) are known in the area (Tab. 1). The Ocna de Fier - Dognecea deposit is perhaps best known as the type locality for ludwigite (Tschermak 1874, Marincea 1999) and for the presence of a large number of unusual Bi- sulphosalt minerals (Ciobanu & Cook 2000).

Nicolescu (1996) inventoried the mineral species which were first described at Ocna de Fier - Dognecea (some of these discredited later):

- veszelyite, discovered by Schrauf the same year as ludwigite (type locality Ocna de Fier – [mindat.org](https://www.mindat.org/));
- "dognacskaite" was described by Krenner (1884) from Dognecea as $\text{Cu}_2\text{Bi}_4\text{S}_7$. It was shown by Koch (1948) to be a mixture of bismuthinite, chalcocite and chalcopyrite;



- "warthaite" ($\text{Pb}_4\text{Bi}_2\text{S}_7$?) was described by Krenner (1925) from Ocna de Fier, but Thompson (1949) showed it to be a mixture of cosalite and galena (synonymous with "goongarrite");
- "tafelspath" (Stutz 1793), renamed by Lemán (1818) wollastonite (wollastonite-1T) on samples from Dognecea; it was then shown that Ciclova and not Dognecea might be the true type locality for wollastonite (see Nicolescu 1996, references therein);
- "rezbanyite" initially described by R. Hermann (1858) from another banatite-related skarn deposit, at Băița Bihor ("Rezbanya") (Apuseni Mountains) - in fact cosalite (Frenzel 1833). Koch (1930) redefined the mineral as $\text{Cu}_2\text{Pb}_3\text{Bi}_{10}\text{S}_{19}$ in samples from Ocna de Fier. Zak et al. (1992) investigated Koch's holotype and showed that the material consists of a mixture of minerals in the bismuthinite - aikinite group (hammarite and krupkaite) and subordinate Cu-bearing cosalite. Thus, "rezbanyite" was formally discredited too (Zak & Mumme 1994). Even thus, bismuth sulphosalts are particularly abundant in the Fe zone and 20 Bi-sulphosalts can today be confirmed from the deposit (Cook et al. 2002).

Several minerals are worth mentioning (Nicolescu 1996), in addition to ludwigite, veszelyite and wollastonite-1T (topotype minerals): cm sized grandite crystals, up to 1 cm magnetite crystals, large hematite rosettes - "iron roses" (up to 8 cm diameter), phlogopite plates (up to several square decimeters, frequently 1 - 2 cm²), large pyroxene (up to 10 cm) and amphibole (exceptionally up to 30 cm, but frequent of 10 cm) aggregates, ludwigite aggregates (2 - 4 cm sized), various pyrite crystal shapes, calcite crystals (~ 30 forms; up to 25 cm large rhombohedra), different bismuth sulphosalts, Japanese and "coaxial" quartz twins.

3.1.4 Skarn type and ore zonation

The Ocna de Fier – Dognecea orefield skarn zonation was a controversial topic. Castle (1896) first reported a transitional trend, involving Fe-oxides to the north (Paulus pit), sulphides and Fe-oxides in the mid, and sulphides to the south (Dognecea). Vlad (1994), Nicolescu & Cornell (1999) attributed this trend to prograde skarn zonation and described grandite-magnetite (calcic-Fe) skarn at Ocna de Fier in the north, mixed grandite-hematite Zn-Pb-(Cu) skarn in the central section, and hedenbergite Zn-Pb-(Cu) skarn at Dognecea in the south. Ciobanu & Cook (2004) considered this trend probably due to several overlapping factors (e.g. the reducing environment offered by the change from gneiss to mica schist at the limestone contact in the south, the extensive replacement of hematite by magnetite). Cook & Ciobanu (2001) proposed an orefield zonation model based on metal distribution, i.e., Cu-Fe/Fe/Zn-Pb (Fig. 5) symmetrically centered onto Simon Iuda. Interpretation of this centric zonation is based upon recognition of a source of fluids in the central and deepest part of orefield, subjacent to the Simon Iuda body.

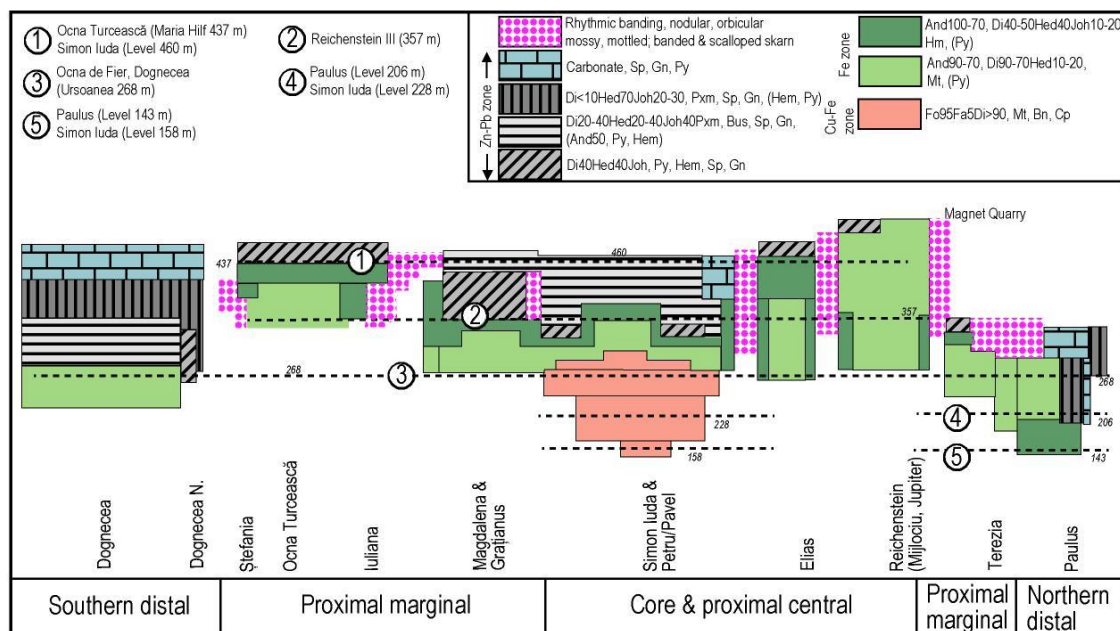


Figure 5: Schematic diagram showing the spatial arrangement, from south to north, of skarn- and ore-types within the individual orebodies of the Ocna de Fier - Dognecea orefield (after Ciobanu & Cook 2004). Corresponding mining levels across the orefield are shown (not to scale).

The patterns are consistent with emplacement outwards and upward from the source of fluids, producing a proximal central segment and distal segments in both north and south (Cook & Ciobanu 2001). Zoning is accompanied by a change in the dominant Fe-oxide from magnetite to hematite towards the outer shells of the Fe-zone in individual orebodies in the central part of the orefield and the presence of hematite rather than magnetite in distal garnet skarn. Such interpretation contrasts with those of other authors (see Ciobanu & Cook 2004). For example, Cioflica et al. (1992) considered that the Cu-ores in the central part of the orefield, i.e., Simon Iuda, were formed after the Fe-ores, from a later surge of fluids that emerged from the granodiorite. This interpretation was an extension of the model introduced by Vlad (1974), who formulated the concept of "individual hot centres". These centres were configured as clusters of apophyses, each linked to the granodiorite, and which provided conduits for fluid springs. Vlad (1994) proposed sequential emplacement for these hot centres, i.e., earliest and hottest in the north, latest and coolest in the south, a pattern that was in agreement with the north to south zonation trend.



3.1.5 Mineralogy of the skarn zones (see Ciobanu & Cook, 2004)

The Cu-Fe core

In the Cu-Fe core the magnesian skarns are located at the very contact of banatite with limestone in the deepest central part at Simon Iuda. Bornite-chalcopyrite-magnetite ores in the Cu-Fe core are hosted by forsterite $\pm$ diopside skarn. The magnetite has characteristics typical of a 'magmatic' affiliation (Zharikov 1970), including MgO contents up to 6 wt%, and fields of exsolved skeletal spinels (Ciobanu & Cook 2004). The forsterite-magnetite-sulphide assemblages are crosscut by clusters of apatite, together with magnetite, sulphides and new forsterite and diopside symplectite-like intergrowths. Apatite is As-bearing type, turneaureite, $\text{Ca}_5[(\text{As},\text{P})\text{O}_4]_3\text{Cl}$ and the coexisting magnetite has up to 6 wt% MnO in the Cu-Fe core. The Cu-Fe core presents a distinctive Fe-Cu-Co-Bi-Ag-Sn-Te-Se-Au geochemical signature. Trace-minerals are found in the Cu-Fe core: high temperature bornitess act as carrier for native Au and Ag, cobalt pentlandite, carrolite, mawsonite, whereas Bi- and Bi-Ag tellurides and selenides are in association with apatite and retrograde forsterite (Cook & Ciobanu 2001).

The Fe zone

In the Fe-zone, the main minerals are garnet, pyroxene, magnetite and hematite. Pyrite is the single sulphide of the prograde associations. Some assemblages can also contain silicates in equilibrium with garnet and pyroxene, such as epidote, tremolite and ferroactinolite. Accessory minerals are phlogopite, ludwigite, serpentine, abundant titanite, and apatite in eutectic equilibrium with calcite. Complex sulfosalt associations are abundant in the Fe-zone and may coexist with associations of prograde stage. Fine intergrowths between Bi-sulphosalts occur either within magnetite or hematite, or in the garnet-pyroxene skarn. Other trace minerals are associated with retrograde overprinting. For instance maldonite (Au_2Bi) has been found only in the Fe ores (Ciobanu and Cook 2004).

The Zn-Pb zone

The main components from the Zn-Pb skarn are pyroxene, sphalerite, galena and pyrite, which coexist with but are more abundant than Fe-oxides, such as hematite and magnetite, Cu-Fe-sulphides, tremolite, garnet and pyroxenoids (bustamite $(\text{Mn},\text{Ca})_3\text{Si}_3\text{O}_9$ and pyroxmangite $\text{MnFe}_2+(\text{SiO}_3)$). The Zn-Pb zone displays a Mn-enriched character shown by the high-johannsenite component of pyroxene (Jo20-40) and by the presence of Mn pyroxenoids.

Textures

A large variety of textures has been formed during the prograde stage. The Cu-Fe core of Ocna de Fier - Dognecea shows only microscopic textures. In the mineral assemblages from the Fe and



Pb-Zn zones and at the marble-skarn contacts, both macroscopic and microscopic patterns can be found: microscopic, oscillatory zonation in garnet and silica bearing magnetite are observed; at macroscopic scale the textures are described as banding, nodular, spotted, orbicular, mossy, and mottled. The most striking patterns are the banded textures called “zebra rocks” which involve magnetite in the Fe and Zn-Pb zones (Ciobanu and Cook 2004). The majority of the retrograde textures are recognisable only at a microscopic scale. Prograde garnet and magnetite from the Fe zone show preserved trace of retrograde textures. Intense brecciation fabrics and fluid-assisted deformation are found in the Zn-Pb zone, whereas the Cu-Fe core displays overprinting textures in the minerals.

P-T conditions

Based on the mineralogical data (forsterite, magnetite and spinel exsolution) Cook and Ciobanu (2001) estimate the temperatures for the prograde proximal skarn in the Cu-Fe core between 500° (lower limit) and 700°C. The peak metamorphic temperature of $700 \pm 50^\circ\text{C}$ decreases away from the contact. The results of thermobarometric experiments point to a pressure of 2.8 ± 1 kbar, equivalent to a ~10 km deep skarn system (Nicolescu and Cornell 1999, Ciobanu and Cook 2004). Observed mineral assemblages (phlogopite, ludwigite, valleriite and apatite) indicate that the skarn formed in a volatile-rich environment.

3.1.6 Orebodies features

The features of the main orebodies (Paulus, Terezia, Magnet, Elias, Simon Iuda, Iuliana, Ocna Turcescă, Aurora, Ferdinand) are presented in Tab. 1 and described by Nicolescu (1996).

Paulus open-pit, Ocna de Fier

Paulus open-pit (Ocna de Fier) is located on the left bank of Moravița, 1250 m north-east of the intrusive body (Fig. 3). Paulus is the northernmost pit of the deposit. The dominant rock types are calcitic and dolomitic marble. Irregular magnetite veins and metre sized lensoid magnetite bodies occur in marbles. Rare earth element (REE) analyses of magnetite reveal slight light rare earth element (LREE) enrichment and unusual negative Ce anomalies suggesting a limestone derived source for magnetite (Nicolescu 1996). The REE profile of the large calcite rhombohedra, with heavy rare earth elements (HREE) enrichment and positive Eu anomaly, indicates the hydrothermal origin of the calcite (Nicolescu 1996).

Terezia open-pit, Ocna de Fier

The Terezia open pit is located 250 m NE of the main banatite body (Fig. 3). The dominant rock type is granditic skarn. Metasomatic textures identified are: grandite concretions in marble,



"orbicular" textures (ring ore - diopside cores surrounded by magnetite rings, all in massive granditic mass) and banded skarns (Liesegang texture - grandite-magnetite, marble-magnetite). Rhomb-dodecahedral garnet crystals, sometimes several centimetres in size, developed at garnet-marble contacts. Cross-cutting the marble, later hematite - quartz veins are developed. In this area Kissling (1967) mentioned the northern-most occurrence of ludwigite. In the north-eastern wall of Terezia Mare pit, several banatite veins occur (gabbro, lamprophyre and granodiorite-porphyry). Minor phlogopite-rich magnesian skarns occur towards the bottom of Terezia Mică pit.

Minerals found at the Terezia pits are garnet, diopside, epidote, tremolite, calcite, quartz, chalcedony, magnetite, hematite, less phlogopite and ludwigite. According to old mine plans and literature, the mineral selection was initially much bigger. At higher levels (now removed) native bismuth, bismuthinite, bismutite, stibnite and greenockite were also found (Nicolescu 1996).

Simon Iuda

Ignaz Edler von Born first mentioned in 1774 the Simon-Iuda mine, described as the richest copper mine in Europe. In a discussion of Born about a paper published in Vienna by Christoph Traugott Delius the features of what later became the contact-metasomatic ore genetic type were mentioned for the first time.

The Simon Iuda orebody is the largest and deepest orebody situated in the central zone of the Ocna de Fier district; it is extended from the surface to 350 m depth. About 2 Mt of the Cu-bearing ores reported from the Ocna de Fier orefield were located in Simon Iuda. The Simon Iuda orebody was described by Cook & Ciobanu (2001), Ciobanu & Cook (2004).

The supergene-enriched Cu-ores were exploited in the 18th century. The ore is situated in the central, proximal part of the orefield, and is interpreted as a volatile-rich core formed immediately above the fluid plume emerging from the source granodiorite (Cook and Ciobanu 2001). This central Cu-Fe zone forms the innermost shell of the deposit and is enveloped by the Fe-zone, which hosts Bi-sulphosalt bearing assemblages (Cook and Ciobanu 2001).

Ursoanea

The Ursoanea waste dump contains excavated material from a transport gallery which connects Dognecea and Ocna de Fier. The gallery crosses the entire skarn area so that its waste dump gathers minerals and rocks of the two major mining fields: phlogopite, ludwigite and other minerals occurring only at Ocna de Fier, and hedenbergite and ilvaite (Vlad 1969, Ilinca et al. 2006) which are characteristic to Dognecea zone.



Iuliana open-pit, Ocna de Fier

This is the largest pit in the area (280 x 150 x 90 m). It is located on the western edge of the limestone syncline (Fig. 3), in the calcic Fe and calcic Zn-Pb (Cu) skarns.

The granditic skarn is extensively replaced by amphibole (tremolite-actinolite) skarn. In vugs and along fissures in the rock pyrite $\pm$ galena, sphalerite and chalcopyrite occur. The main ore mineral in the quarry is hematite (specular "iron roses", several centimetres in diameter). Often the hematite is accompanied by quartz crystals. Iuliana pit is the southernmost occurrence of ludwigite at Ocna de Fier. Ludwigite forms decimetre thick bands, associated with magnetite and serpentine.

Rare earth element data were collected on several mineral species from Iuliana (Nicolescu & Cornell 1996). REE profiles of both individual grandite zones and bulk granditic skarn have similar features. The garnet REE content is low and the chondrite normalised profiles show LREE enrichment and negative Ce and Eu anomalies, features similar to those of carbonate rocks and magnetite in the deposit, and also to modern sea-water (Nicolescu 1996). REE profiles of both intrusive and metamorphic rocks in the area have typical granodiorite and metapelite patterns respectively. These data strongly suggest that, at least partly, the skarn mineralising fluids and the associated metals were limestone-derived and not of magmatic or metamorphic origin (Nicolescu 1996). The REE pattern of tremolite from the Iuliana pit has positive Eu anomaly and even lower contents than garnet, suggesting its formation at a different (later) stage, from other fluids than the ones from which the grandite precipitated (Nicolescu 1996).

Mineral species described at Iuliana pit are andradite-grossular, tremolite-actinolite, diopside, forsterite, phlogopite, epidote, talc, calcite, ludwigite, serpentine, magnetite, hematite, pyrite, galena, sphalerite, chalcopyrite, marcasite, bornite, quartz.

Ferdinand mine dump, Dognecea

The main mineralogical differences between Ocna de Fier and Dognecea fields are the dominance of pyroxene (mainly hedenbergite - manganoan hedenbergite) over garnet and the sulphidic character of the mineralization at Dognecea.

The Dognecea sector of the deposit was mined mostly underground. The Ferdinand mine extended for 7 km along the whole length of the deposit, from Ocna de Fier to Dognecea. Thus, the dump at this southern end of the mine hosts a collection of all rock types and many minerals occurring in the deposit. Besides the already mentioned mineral species, hedenbergite and ilvaite and their manganoan varieties are characteristic for Dognecea. Hedenbergite is abundant, usually associated with sulphides. It occurs in large dark-brown or brown-black radial aggregates, with prismatic crystals frequently 8 - 10 cm long.



3.2 Oravița-Ciclova

Cu (ZnPb) skarn deposit from Oravița-Ciclova was mined from ca. 1400 to 1989. In 1764, Oravița produced 140 t Cu and 234 kg Ag (Tăutu, 2009). Currently, exploration for polymetallic ores is undertaken at Ciclova. Subeconomic porphyry copper ($\pm$ Mo) accumulations are present at Oravița.

A comprehensive description of the geological setting and mineralogy of the skarn outcrops on the northern slope of Țiganilor Valley, Ciclova is presented by Ilinca et al. (2011). The skarn deposit is mainly related to the plutonic banatites cross-cutting a carbonate rock sequence belonging to the sedimentary cover of the Getic unit (Fig. 2, 6) in the eastern part of the zone. Less skarns (grandite) and calcsilicate hornfels are banded parallel to the contact between the crystalline schists of the Bocșița-Drimoxa Formation (Bocșa Nappe) in the western part and the limestones which is similar to the sequence from Ocna de Fier - Dognecea. The banatitic bodies consist of early diorites, monzodiorites and isolated gabbros (Oravița Valley and Ciclova), and subsequent porphyritic granodiorites (Maidan and Tâlva Mică, north of Oravița Valley). Small bodies of lamprophyres, andesites, sienites, alkali-granites, rhyolites and dacites (dykes) are randomly distributed throughout the main igneous bodies and the sedimentary formations. Extensive hydrothermal alteration and related copper-dominant mineralization were recognized associated with the banatitic intrusions.

More than 120 minerals were described at Oravița-Ciclova, with a case of type locality – hörnesite, and as also for the discredited mineral csiklovaite (see Ilinca et al. 2011). Ilinca et al. (1993) published a historical list of minerals described at Oravița - Ciclova.

The skarn deposit includes occurrences of high-temperature skarn minerals gehlenite (Constantinescu et al., 1988; Katona et al., 2003), vesuvianite, wollastonite, scheelite, Ti-rich calcic garnet, Ti-poor calcic garnet, åkermanite-rich melilite, monticellite, Al-rich diopside, magnetite, perovskite, a Ca-Si mineral (kilchoanite?), clintonite, fukalite, katoite, hydroxyllestadite (Marincea et al. 2015), and a rich assemblage of Bi-sulphosalts including proudite, lillianite homologues, felbertalite, bismuthinite derivatives, cannizzarite, makovickyite – cupromakovickyite, kupčikite, emplectite, junoite, cosalite and various tellurides and sulphotellurides (Ilinca 1998). More details are found in Ilinca et al. 2011, Marincea et al. 2015.



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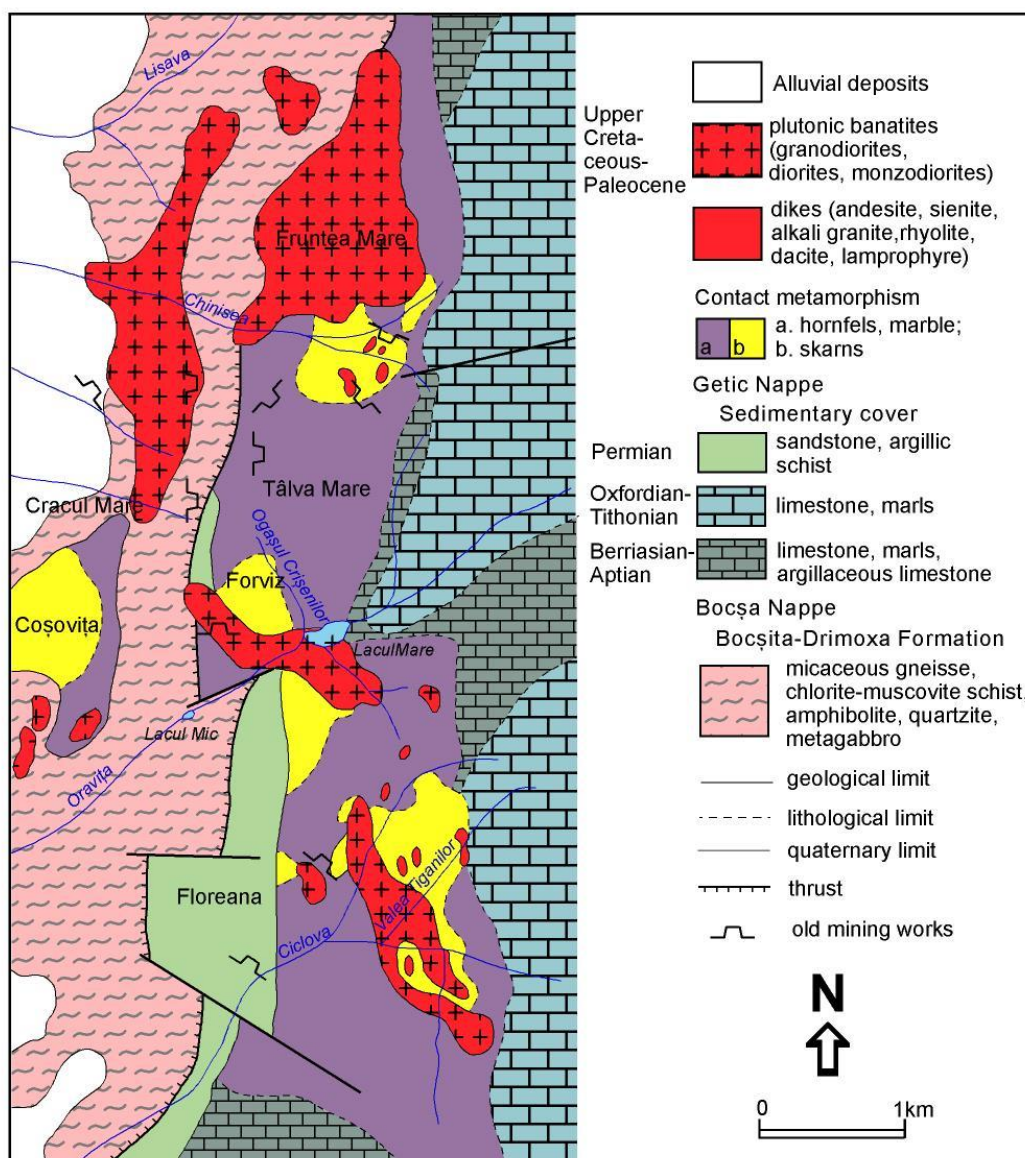


Figure 6: Geological sketch of Oravița – Ciclova area (after Ilinca et al. 2011 and references therein and 1: 50 000 Resița map of Geological Institute of Romania)



3.3 Sasca-Montană

The mineralisation occurs along the contact of granodiorite-quartz diorite bodies with Mesozoic limestones, generating skarns with andradite-grossularite, vesuvianite, wollastonite, diopside and scapolite; hydrothermal processes produced tourmaline, fluorite, mica, smectite, kaolinite, serpentine, talc, actinolite, chlorite and zeolites (Constantinescu, 1980; Dimitrescu, 1983). The ore occurs as shallowly-dipping tabular concordant bodies ("manto" type), lens-shaped bodies, mineralized breccia pipes and irregularly-shaped bodies (Dimitrescu, 1983). The endoskarns contain pyrite, chalcopyrite, magnetite and molybdenite; this assemblage occurs in the exoskarns, joined by bornite, digenite, pyrrhotite, arsenopyrite, native gold, sphalerite, acanthite, and hematite; the thermally metamorphosed limestones also contain galena, tetrahedrite, enargite and jamesonite; breccia pipes contain pyrite, marcasite, chalcopyrite and sphalerite (Constantinescu, 1980; Dimitrescu, 1983).

Sasca Montană was a flourishing metallurgical center, with four metallurgic factories in 1760 and a production of 200 t metallic copper in 1770, which made it the greatest copper producer in Banat (Tăutu, 2009). The old waste rock dumps at Sasca Montană were re-mined during the 1700s (Tăutu, 2009). Ore extraction showed a continuous decline after 1870s and mining ceased in 1905 (Grăf, 1997). The mining of copper ore was resumed in 1972 and stopped in 1998; in this interval, ca. 1.736 Mt of ore was extracted at average grade of 0.75%, resulting in an average annual copper production of 513.7 t.

Several samples from the uppermost 3 m of the tailings pond at Sasca Montană showed contents of 0.1-0.2% Cu, 0.02-0.03% Zn, 3-8 g/t Bi, 10-20 g/t Co, 14-30 g/t Mo, 17-26 g/t Ni, <5 g/t Sb, 1-2 g/t Ag (authors unpublished data). A test of gravitational concentration of the tailings from Sasca Montană produced a concentrate representing 6.18% of the sample mass, which contained 0,9 g/t Au, 2 g/t Ag, 0,81% Cu, 0,011% Pb and 0,78% Zn (ICPMRR, 2017).

3.4 Moldova Nouă

Moldova Nouă Cu (AuMo) deposit belongs to the southernmost segment of the BMMB in Romania (Fig. 2).

The geology of Moldova Nouă segment (Fig. 7) is characterized by N-S hypabyssal granodiorite and quartz-diorite bodies with eastern vergence (Vlad 1983) crosscut the sedimentary formations represented by Jurassic sequence (Oxfordian-Tithonian and Berriasian-Aptian) limestones and marls (see Ilinca et al. 2011, references therein). Contact metamorphism around banatitic bodies led to marbles, biotite-andalusite-actinolite or diopside-biotite hornfels, garnet-diopside-vesuvianite and diopside-plagioclase endoskarns, wollastonite-garnet-pyroxene-chondrodite exoskarns, etc. High-temperature, pervasive potassic hydrothermal alteration occur in the main granodiorite body (Suvorov Valley) (more details in Ilinca et al. 2011). Ore deposits occur as irregular bodies along magmatic contact. The mineralization consists of chalcopyrite, pyrite, magnetite with minor molybdenite, sphalerite and tetrahedrite and it is



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differentiated against the host hydrothermal alteration (see Ilinca et al. 2011). Potassic zones are associated with magnetite impregnations and subordinate chalcopyrite and pyrite. Propylitic alteration contains mainly magnetite disseminations with traces of chalcopyrite and pyrite. Phyllic areas are dominated by mineralized veinlets with pyrite, chalcopyrite $\pm$ sphalerite, molybdenite or pyrite $\pm$ tetrahedrite, with the later surrounded by impregnations of pyrite and chalcopyrite. The upper parts of the porphyry complex host supergene transformation areas of up to 5-10 m thick, with kaolinite, illite, montmorillonite, copper carbonates and sulphates.

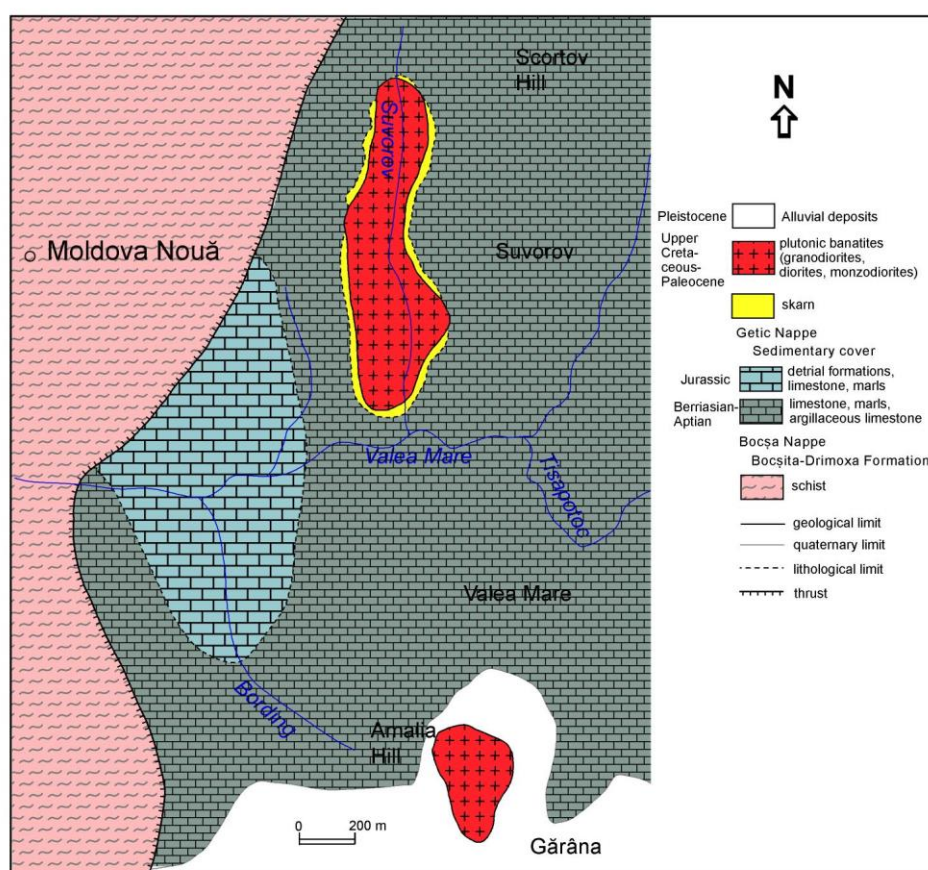


Figure 7: Geological map of Suvorov area, Moldova Nouă (after Ilinca et al. 2011).

After the Roman period, mining has been resumed at Moldova Nouă at latest from ca. 1600, under the Ottoman administration (Ilieșiu, 2011), and was reorganized during the Habsburg administration. Mining in Moldova Nouă had a relative slow development, with numerous interruptions because of the frequent Habsburg-Ottoman conflicts, which resulted in repeated destruction of the mine equipment, whereas Moldova Nouă was the mine closest to the border



between the two empires, as compared to the other mining areas in Banat. The extracted ore produced ca. 13 t Cu in 1764 and ca. 45 t Cu in 1770 (Tăutu, 2009). Skarn mineralisation was exploited by underground methods until the early 1970's when porphyry Cu mineralisation became to be recognized as significant ore type. Subsequent open pit operations in Suvorov area (Fig. 7) have been conducted (Vlad 2011). In 1970s and 1980s, the ore production resulted jointly from the porphyry-type mineralisation (0.23-0.35% Cu), extracted in open pit, and the skarn mineralisation (0.7% Cu - similar to the one at Sasca Montană), extracted underground (USGS, 1992). The mixture of the two ore types resulted in productions of ca. 5-6 Mt tons/year at ca. 0.42% Cu (= 80,000 t concentrate at 14% Cu), <2 g/t Au and 0.055% Mo, in the interval 1984-1990 (USGS, 1992). The Suvorov body may be considered as representative for the Banatitic porphyry copper systems. The total estimated porphyry copper ore is 500 Mt at 0.35% Cu (1,800,000 t copper metal), with Au, Ag, Se and Mo as minor commodities (Sutphin et al., 2013). Cheșu (1983) mentioned contents of 0-20 g/t In in the ore, 1-100 g/t In and 0-50 g/t Ge in the pyrite concentrate, 0-300 g/t Co in copper concentrate, 0-1500 ppm Ni in tailings. Cd contents in the copper concentrate were of the order of thousand ppm (Cheșu, 2003). The deposit is currently under mining license but the mining activities are stopped.

Several samples from the uppermost 3 m of the tailings pond at Moldova Nouă showed contents of 0.1% Cu, 0.03-0.05% Zn, 5-8 g/t Bi, 17-24 g/t Co, 11-39 g/t Mo, 22-40 g/t Ni, 10-24 g/t Sb, 1 g/t Ag (authors unpublished data).

4 Conclusions

The ore deposits from Banat have been exploited since ancient times, with the peak production and industrial significance in the 18th and 19th centuries (considering the aggregated production of all mining areas). The high grade ore in these deposits is exhausted but lower grade ore, at least in some of them, is tempting enough to motivate new exploration. The potential of secondary resources (mine waste rock dumps, tailings ponds, and metallurgic slags) is worth more extensive investigation.



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