

# General features of some polymetallic ore deposits in the Republic of North Macedonia

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## Abstract

The general features of several important mineral deposits of polymetallic character in the Republic of Northern Macedonia that have been actively exploited in the past are described. These include the Buchim copper mine and Sasa, Zletovo and Toranica lead-zinc mines, as well as some ore prospects that have been extensively explored for years. In addition, sites with known ore reserves, but which are not yet at the exploitation stage are presented, including Plavica, Ilovica, Kadiica, Borov Dol and others. The elaborated RIS-RESERVES program is used to affirm numerous parameters related to the definition of ore reserves in the deposits, and has now provided the opportunity for preparation of an overview which shows the major metallogenetic characteristics of the deposits with their techno-economic parameters. This approach enables affirmation of the potential of the polymetallic ore deposits in the Republic of Northern Macedonia.

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## 1. INTRODUCTION

The polymetallic ore deposits in the territory of the Republic of North Macedonia from the geotectonic, structural, magmatic and metallogenetic point of view belong to the large geotectonic and metallogenetic units such as the metallogenetic belts, provinces, zones, regions etc. The Tethys-Eurasian metallogenetic belt is of special importance in metallogenetic zoning, which combines polymetallic mineralization of different rank and intensity, but with similar magmatic and mineralization features (JANKOVIC, 1977; SERAFIMOVSKI, 1993; MORITZ & BAKER, 2019). The polymetallic mineralization from the regional point of view belong to the Alpine-Balkan-Carpathian-Dinarides metallogenetic belt (HEINRICH & NEUBAUER, 2002). The Serbo-Macedonian Metallogenetic province, which occupies central parts of the Balkan Peninsula, is a large metallogenetic unit with typical polymetallic ore deposits in the territories of Serbia, the Republic of North Macedonia and Greece (JANKOVIC et al., 1980; SERAFIMOVSKI, 1993; ARVANITIDIS, 2010). The Lece-Chalkidiki metallogenetic zone is especially important for the temporal and spatial distribution of polymetallic ore deposits at the contact parts of the Serbo-Macedonian Mass (SMM) and the Vardar Zone (VZ) including the Macedonian ore deposits (JANKOVIC, 1990; SERAFIMOVSKI, 1990; SERAFIMOVSKI, 1993; ALDERTON & SERAFIMOVSKI, 2007). Regional geotectonic structures NNW-SSE and Tertiary volcanic intrusions and extrusions are very important for the distribution of polymetallic ore deposits in the Central Part of the Balkan Peninsula, see also (ARSOVSKI & IVANOV, 1977; KARAMATA, 1983; SERAFIMOVSKI, 1993; SERAFIMOVSKI et al., 2003; JELENKOVIC et al., 2008; VOLKOV et al., 2019). In the territory of the Republic of North Macedonia, polymetallic mineralizations are paragenetically related to the Tertiary volcanic intrusions of calc-alkaline character (16-37 Ma; HARKOVSKA et al., 1989; BOEV & YANEV, 2001; SCHEFER et al., 2011), as well as the various tectonic structures trending in a NNW-SSE direction (IVANOV,

1966; SERAFIMOVSKI, 1993; SERAFIMOVSKI et al., 1997; DUMURDZANOV et al., 2005; SCHMID et al., 2013) and lithostratigraphic complexes representative of the Serbo-Macedonian Massif and Vardar Zone in these terrains (BURCHFIEL et al., 2008a; BURCHFIEL et al., 2008b; LEHMANN et al., 2013; PETRUŠEV et al., 2021).

## 2. REGIONAL GEOTECTONIC AND METALLOGENIC SETTING OF THE MACEDONIAN POLYMETALLIC ORE DEPOSITS

The studied polymetallic deposits in the Republic of North Macedonia belong to two large geotectonic units; the Vardar zone to the west and to the east the Serbian-Macedonian Massif and they occupy the central parts of the Balkan Peninsula extending in a general northwest-southeast direction. The geological and geotectonic setting of these two large geotectonic units has been studied by DIMITRIJEVIC (1958), JANKOVIC (1977), ARSOVSKI & IVANOV (1977), SERAFIMOVSKI (1993), DUMURDZANOV et al (2005), ROBERTSON et al., (2009). ), LEHMANN et al., (2013), SCHIMDT et al., (2013), ANTIC et al., (2016) and ŠOSTER et al., (2020). The Vardar zone is treated as a zone of ophiolitic melange, while the Serbian-Macedonian Massif is described as a rigid mass built of Precambrian rocks that make up the base and Palaeozoic shales. In the post-collision processes in both settings, Oligo-Miocene volcanism took place (BOEV & YANEV, 2001) with which the polymetallic deposits in Macedonia and adjacent regions are associated (SERAFIMOVSKI et al, 2003; ALDERTON & SERAFIMOVSKI, 2007 Fig. 1).

From a metallogenetic point of view, the polymetallic mineralizations on the territory of the Republic of North Macedonia belong to a part of the Lece-Chalkidiki metallogenetic zone, which is completely defined by SERAFIMOVSKI (1990), and it covers the contact parts between the Vardar zone and the Serbo-Macedonian massif (Fig. 1), while the other part belongs to the

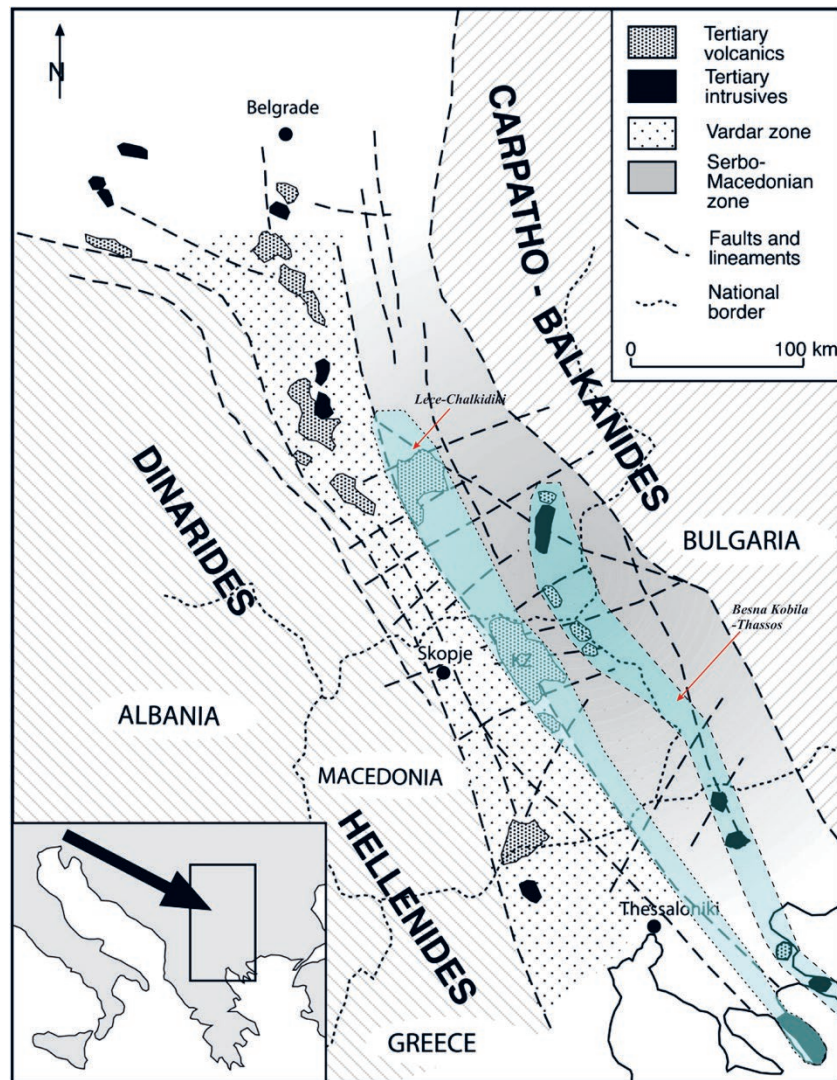


Figure 1. The Location of Tertiary volcanics and major metallogenetic units in the southern part of the Balkan Peninsula (after ALDERTON & SERAFIMOVSKI, 2007).

metallogenetic zone Besna Kobila-Osogovo-Thassos defined by SERAFIMOVSKI (1990) and ALEKSANDROV (1992). This zone is completely located in the terrains of the Serbo-Macedonian Massif. Both zones have a general direction of northwest-southeast beginning in Serbia and continuing through Macedonia to Northern Greece. Their main features are Tertiary volcanic rocks, regional fault structures with a northwest-southeast direction and polymetallic mineralizations such as lead, zinc, copper, gold, silver, molybdenum and others. The first data for the Lece-Chalkidiki zone appear in the works of JANKOVIC et al (1980), and later in the works of SERAFIMOVSKI (1993), ALDERTON & SERAFIMOVSKI (2007) and VOLKOV et al. (2019), while for the Besna Kobila-Osogovo-Thassos metallogenetic zone more detailed information can be found in the works of TASEV (2010) and TASEV et al. (2019).

### 3. POLYMETALLIC ORE DEPOSITS IN THE REPUBLIC OF NORTH MACEDONIA

Almost all Alpine polymetallic ore deposits in the Republic of North Macedonia are related to the major geotectonic units (Vardar Zone-VZ and Serbo-Macedonian Mass-SMM) and metallogenetic units (Serbo-Macedonian metallogenetic province). The enclosed Lece-Chalkidiki and Besna Kobila-Osogovo-Thassos

metallogenetic zones have an emphasized significance in regard to the polymetallic ore deposits (Fig. 2).

In terms of the production of lead, zinc and copper in the territory of the Republic of North Macedonia the ore regions of Kratovo-Zletovo, Sasa-Toranica, Damjan-Buchim, are particularly important as well as the ore fields Kadiica and Ilovica (SERAFIMOVSKI, 1993; TASEV, 2010; FORWARD et al., 2017). The ore veins in the Zletovo deposit, as well as the quartz-graphite series in the Sasa and Toranica deposits are bountiful from the aspect of lead and zinc production (SERAFIMOVSKI & ALEKSANDROV, 1995). Copper ores are abundant in the Buchim (ČIFLIGANEC, 1993) and Borov Dol (VOLKOV et al., 2010; GJORGIEV, 2020), while in terms of potentiality, the Plavica (SERAFIMOVSKI et al., 2017), Kadiica (TASEV, 2010) and Ilovica deposits (FORWARD, 2017) are interesting. Some of the more significant metallogenetic characteristics of these deposits are presented in the following section.

#### 3.1. Plavica

The area where the Plavica deposit mineralization is located is a classic volcanic cone, which is part of the famous Tertiary volcanism in the Zletovo-Kratovo volcanic area (STOJANOV, 1980). It consists of ignimbrite, dacite-andesite volcanic tuff, breccia and dacite-andesite as well as quartz-latite intrusions which form the

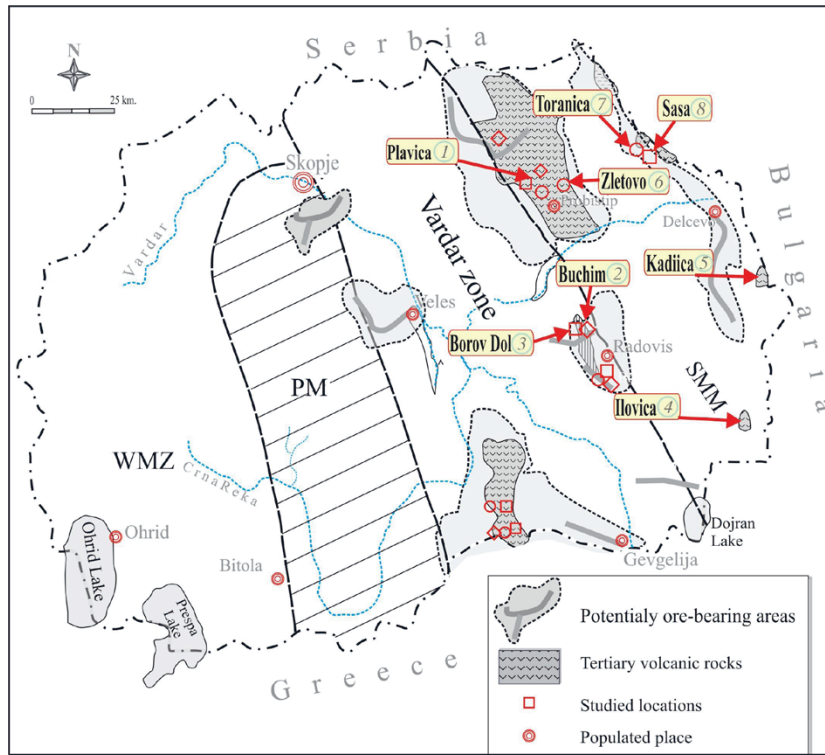


Figure 2. Location of the polymetallic deposits in the territory of the R. N. Macedonia (after TASEV, 2003). WMZ-Western Macedonian Zone; PM-Pelagonian massif; SMM-Serbo-Macedonian Massif

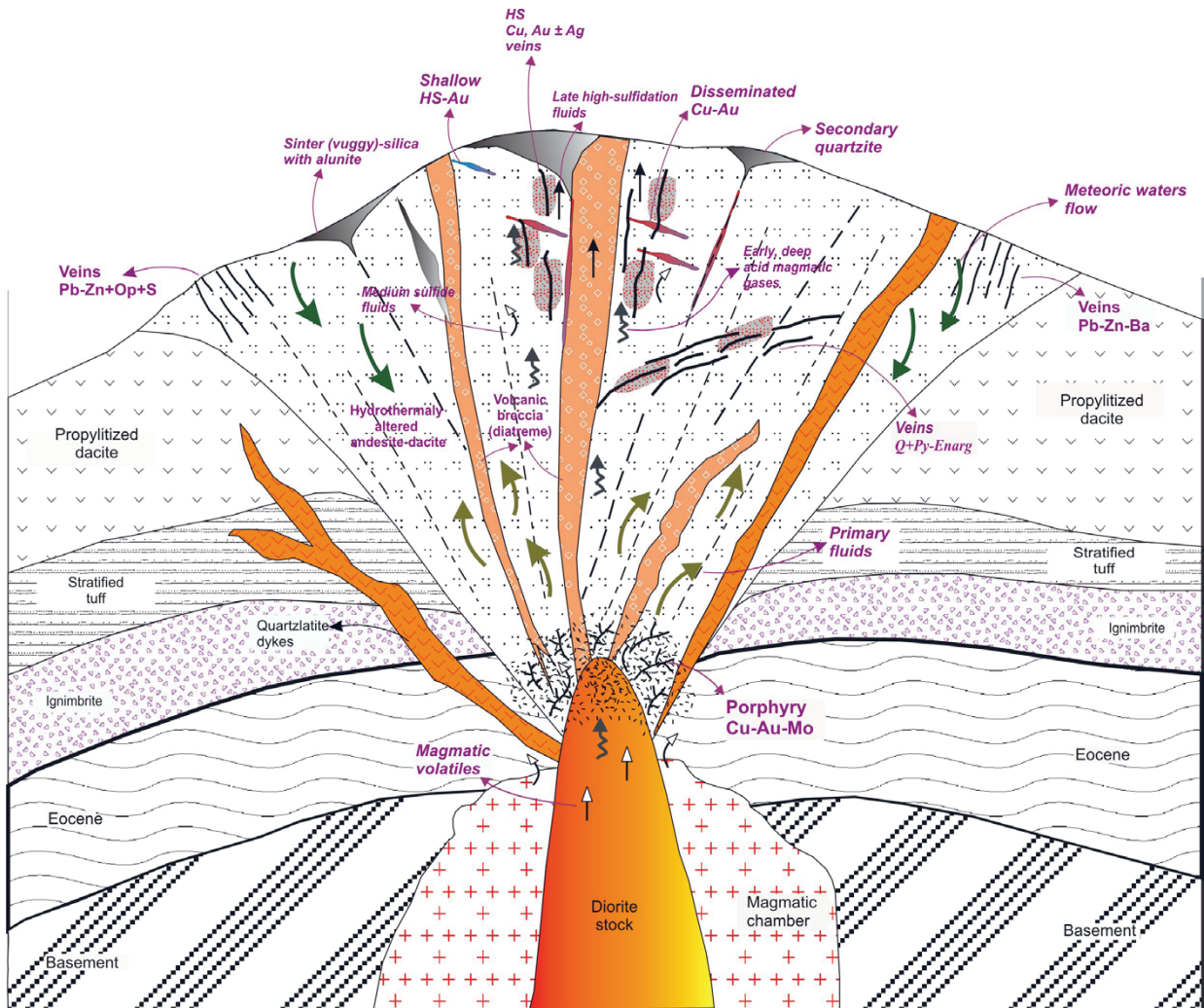


Figure 3. Schematic genetic model of the Plavica Cu-Au polymetallic ore deposit (after SERAFIMOVSKI et al., 2017). HS-high sulfidation; Op-opalization

basis of the lithological structure of the Plavica volcanic apparatus (SERAFIMOVSKI et al., 2017; Fig.3), which resembles a typical volcanic caldera that is degraded on its southern side (MARKOVIC, 1971; SERAFIMOVSKI, 1990).

The general characteristic of the mineralized part of the Plavica is the intense hydrothermal alteration which is dominated by kaolinization, sericization, silicification and allunization. Several types of mineralization have been identified as part of a long research process that began intensively in 1971 and continues to this day with some interruptions. Porphyry copper mineralizations have been of primary interest, but the remains of the old mining (primarily adits) attest to the fact that the quartz-pyrite-energite veins were exploited in Roman times and in the period after World War II (IVANOV & DENKOVSKI, 1978; IVANOV & DENKOVSKI, 1980). Gold-bearing mineralizations in the quartz-alunite zones (vuggy silica) are of economic interest with the gold content of up to 3 g/t Au (SERAFIMOVSKI & RAKIC, 1999). In the northwestern and southeastern peripheral parts of the mineralized volcanic apparatus, thin lead-zinc veins have been registered, which continue towards the southeast and the Zletovo deposit. The economic parameters for the Plavica deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to Republic North Macedonian standard) and their summary is in Appendix 2; Table 1.

### 3.2. Buchim

Buchim has long been the only copper mine not only in Macedonia, but also in the Lece-Chalkidiki zone. Copper ores of the porphyry type with characteristically low contents of 0.25% Cu and 0.3 g/t Au have been exploited for more than 40 years (ČIFLIGANEC, 1993; VOLKOV et al., 2010). The porphyry cop-

per ores in the Buchim deposit are spatially localized around the andesitic intrusions in the Precambrian gneiss and amphibolite (SERAFIMOVSKI, 1993). The Tertiary volcanic intrusions aged 27-24 Ma (LEHMANN et al., 2013) intruded in the form of dykes and necks in the Precambrian complex 27-24 Ma ago. Three types of copper mineralization are distinguished in the Buchim deposit: primary chalcocopyrite, secondary deposits? in the cementation zones (chalcocite-covellite; secondary sulfide enrichment) and a mixed deposit localized mainly in the Vršnik ore body (ČIFLIGANEC, 1987; ČIFLIGANEC, 1993; STRMIĆ PALINKAŠ et al., 2022). Cu-Au mineralization is associated with hydrothermal alteration assemblages within and around the ore body as it is shown for the youngest Buchim ore body of Vršnik (STRMIĆ PALINKAŠ et al., 2022). The productive remaining mineralization of the porphyry ores in the Buchim mine is located in the Bunardzik and Cukar 2 East ore bodies (Fig. 4).

The potential of the Buchim ore deposit from the aspect of primary mineralization can be observed below the 405 m level, where the mineralization shows continuity in distribution. The economic parameters for the Buchim deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia standard) and their summary can be found in Appendix 2; Table 1.

### 3.3. Borov dol

The Borov Dol deposit spatially belongs to the Vardar zone Different phases of Tertiary volcanic rocks, 32-27 Ma, where stratified volcanic tuffs and volcanic breccia participate in its lithological construction (TUDZAROV, 1993; LEHMANN et al., 2013). Porphyry copper mineralization is localized around the fine-grained andesite that has intruded the coarse-grained altered

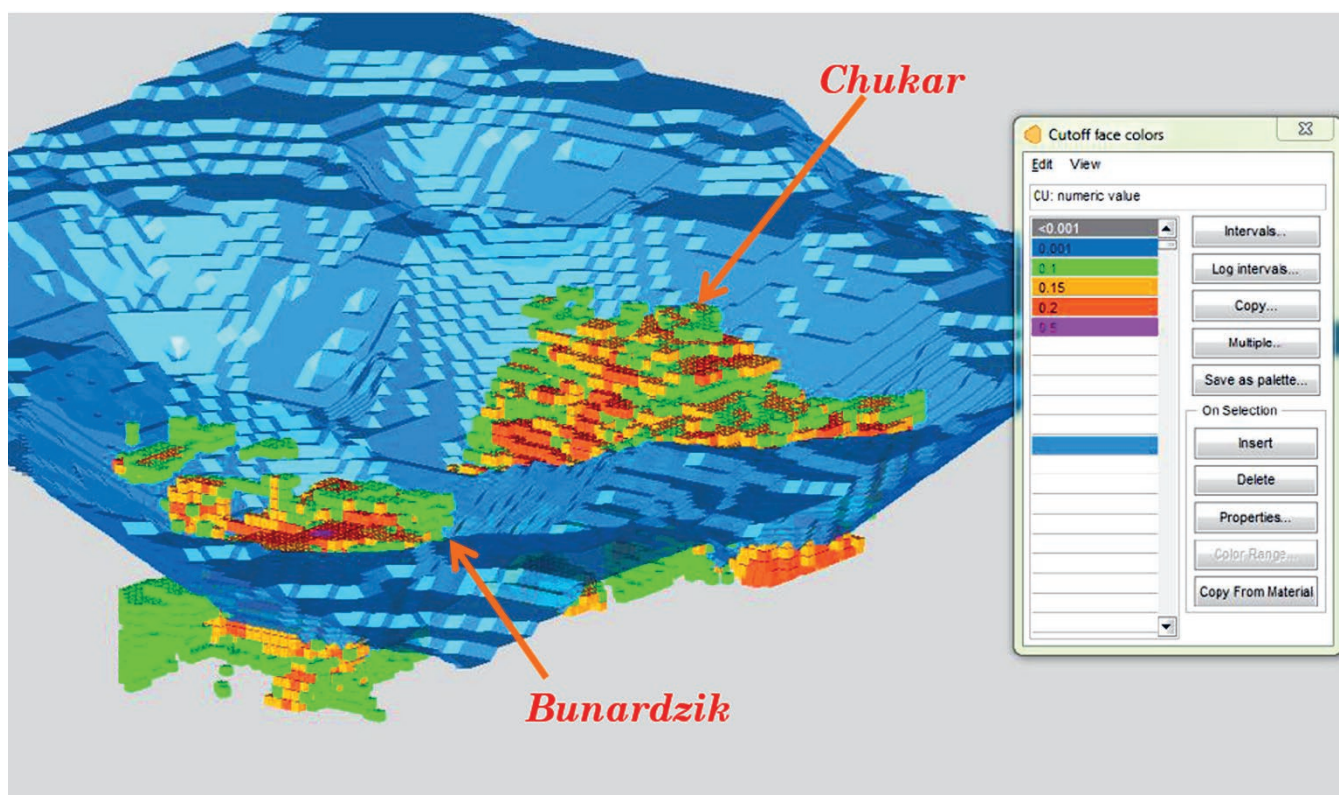


Figure 4. A 3D model of the Cu grades of Bunardzik and Chukar ore bodies within the Buchim Mine, looking Northeast (after GRAY et al., 2017).

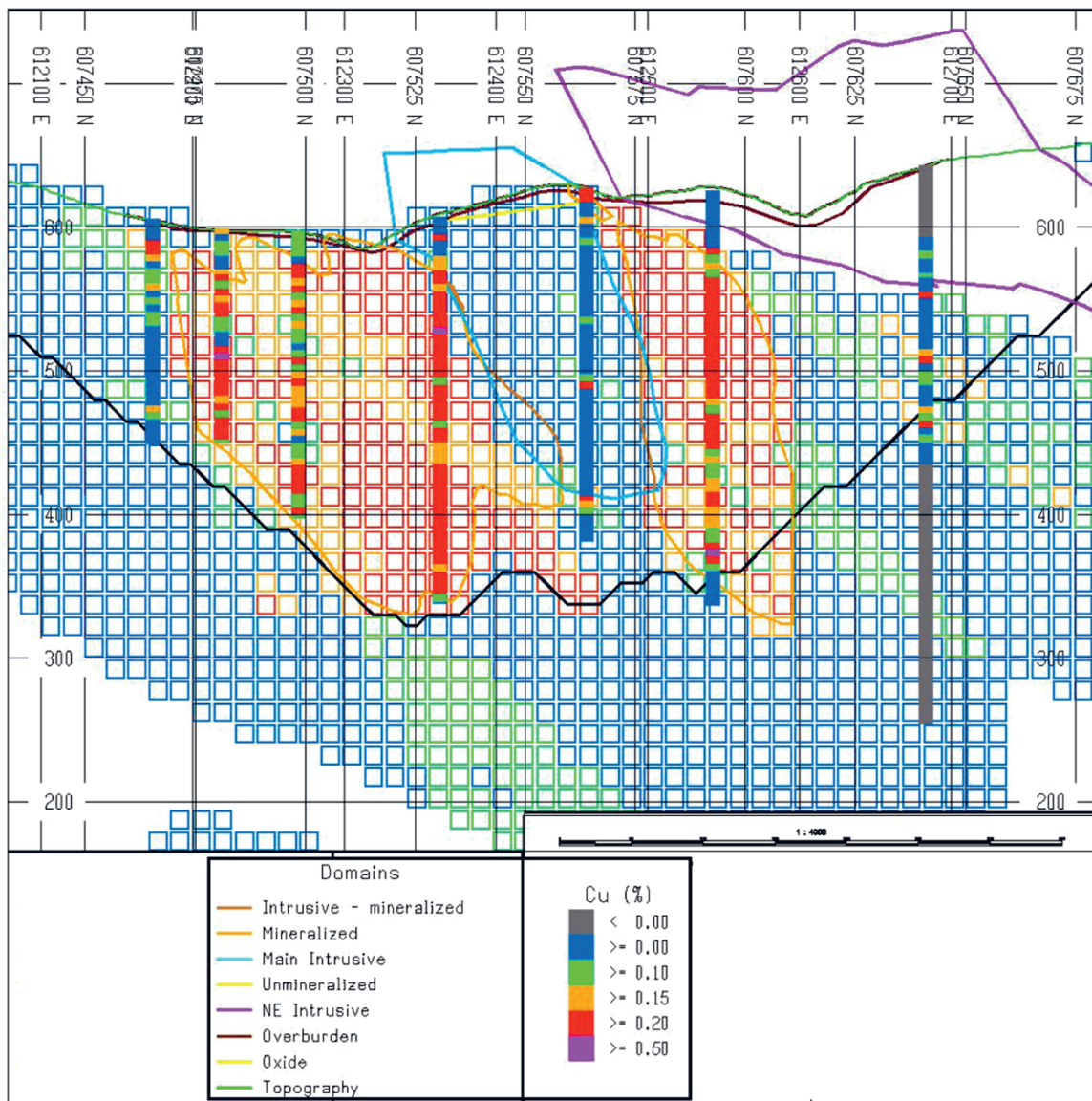


Figure 5. A visual presentation of assay and modelled Borov Dol copper grades (after GRAY et al., 2017).

andesite (Fig. 5) containing copper mineralization averaging 0.3% Cu and 0.3 g / t Au (SERAFIMOVSKI, 1993).

Kaolinization, silicification and sericitization are the most intense hydrothermal alterations of the volcanic rocks while the higher parts are affected by epidotization, chloritization and limonization (KNEŽEVIĆ et al., 1975; GJORGJIEV, 2020).

The porphyry copper mineralization style is defined by a genesis study of the Borov Dol deposit, especially fluid inclusions, isotope compositions, geochronological and alteration type studies. Primary ore solutions were defined by carbon and oxygen isotopes (TUDZAROV & SERAFIMOVSKI, 1994; TUDZAROV & SERAFIMOVSKI, 1995) and sources of metal by the sulfur isotope compositions (SERAFIMOVSKI, 1993; SERAFIMOVSKI & TASEV, 2013; GJORGJIEV, 2020). Geochronological data were defined by LEHMANN et al., (2013). The economic parameters for the Borov Dol deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) and their summary can be found in Appendix 2; Table 1.

### 3.4. Kadiica

Kadiica-Bukovic is one of the few, if not the only, porphyry copper mineralization located in the easternmost metallogenetic zone of Besna Kobila-Osogovo-Thassos, which is mainly dominated by the mineralization of lead and zinc sulfides, sometimes followed by the appearance of scheelite and molybdenite (JANKOVIC & PETKOVIC, 1974; JANKOVIC et al., 1980; SERAFIMOVSKI et al., 1995; TOMSON et al., 1998).

The geological composition of the Kadiica deposit is represented by Eocene-Oligocene quartzlatites (35-27 Ma; HARKOVSKA, 1984; HARKOVSKA et al., 1989) and hydrothermally altered schist (STOJANOV et al., 1995; TASEV, 2010). Copper-bearing mineralization is mainly manifested as secondary chalcocite and covellite that occur in the form of pyrite coatings and less frequently chalcopyrite in the form of stockworks and disseminations (TASEV, 2010). The identified mineralizations clearly define the zones of leaching and secondary sulfide enrichment (Fig. 6).

Morphostructural analysis classifies ore bodies as poor hypogenic copper mineralizations (<0.15% Cu) and richer ore bodies of secondary sulfide enrichment of copper (with average cop-

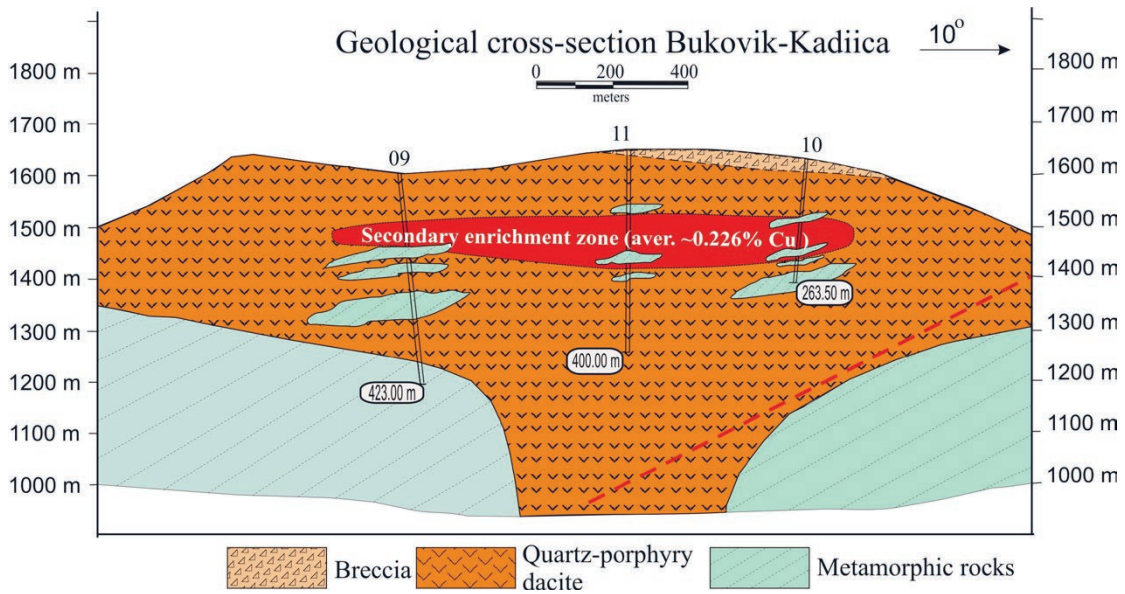


Figure 6. A geological cross-section at Bukovik-Kadiica (after TASEV, 2010). Note: Exploration drill holes 09 (depth 423 m), 10 (depth 400 m) and 11 (263.5 m)

per concentrations of around 0.22% Cu). Hypogenic mineralization is of a disseminated stockwork character with variable contours. At depth, copper mineralization occupies a space between the 90 and 220 m levels (TASEV, 2010). Calculated ore reserves and the associated economic parameters of Bukovik-Kadiica were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) and summarised in Appendix 2; Table 1.

The study of the fluid-inclusions within quartz associated with the mineralizations confirmed that the formation of the copper mineralization in the Kadiica deposit took place over a wide temperature range (627-326 °C) and with three main composi-

tional phases of the ore solutions. The solutions were characterized by different salinities i.e. from 6-16 wt% NaCl through 3-24 wt% NaCl equiv to those with 32-45 wt% NaCl (TASEV, 2010; TASEV et al., 2018)

### 3.5. Ilovitsa

The porphyry Cu deposit of Ilovitsa is another example of mineralization within the Lece-Chalkidiki-Thassos metallogenic zone (SERAFIMOVSKI, 1990; HEINRICH & NEUBAUER, 2002; TASEV, 2003). The geological basis of the Ilovitsa ore deposit is composed of Precambrian (two-mica gneiss, biotite gneiss, muscovite gneiss, mica-schist and amphibolite) and Rhiphean-Cambrian (amphibolite and epidote-quartz-sericite-chlorite schist) rocks. At the time of the Palaeozoic (Hercynian orogeny)

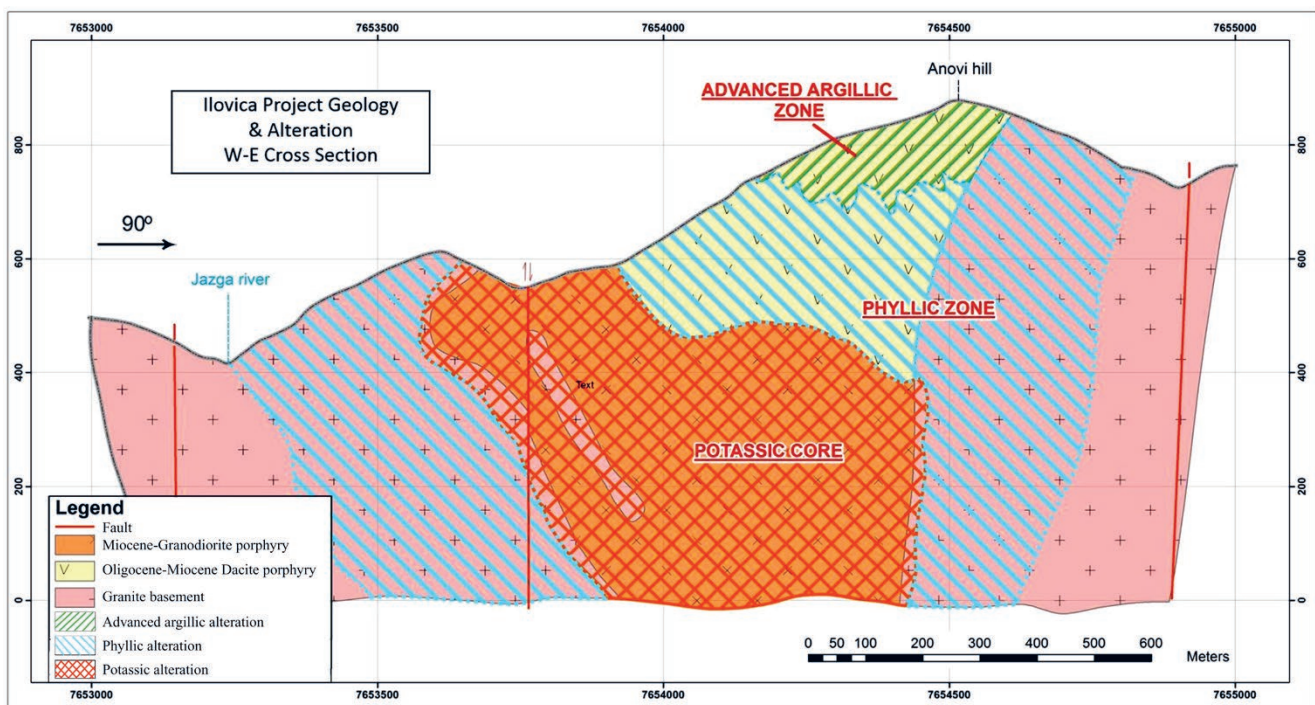


Figure 7. Ilovitsa ore deposit geological cross-section and alterations, west-east cross section (after FORWARD et al., 2017).

this foundation was intruded by granite in the form of batholiths. Later in the Late Eocene-Oligocene this area was protruded by dacites and andesites, which are characterized by mineralization of economic or non-economic character (Fig. 7).

The Tertiary rocks are affected by hydrothermal alterations, which in places lead to the complete destruction of the primary structures and change of the initial mineral composition. These alterations are manifested by an advanced argillic zone, phyllic zone and potassic core, while silicification, sericitization, alunitization, opalization and chloritization were rarely determined (Fig. 7). The mineralization is associated spatially and genetically with a granodiorite stock that occupies a surface area of 100 x 200 m (100 m to the north-south and 200 m to the east-west), while at depth can be detected down to approximately 700 m. The main ore minerals of the stockwork mineralization are: chalcopryrite, pyrite, bornite, native gold, magnetite, haematite, tennantite, galena, sphalerite, chalcocite, covellite, etc. A cementation zone formed below the oxidation zone, and has a thickness in the range of 3.5 to 9 m, and the main ore minerals are chalcocite and covellite (SERAFIMOVSKI, 1993; SERAFIMOVSKI & TASEV, 2011). The economic parameters for the Ilovitsa deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) and are summarised in Appendix 2; Table 1.

### 3.6. Zletovo

The lead-zinc deposit of Zletovo is a typical vein type hydrothermal deposit of subvolcanic character, localized in the ignimbrite and tuff of Tertiary age which are intruded by dacite and andesite dykes and necks [SERAFIMOVSKI, 1993; SERAFIMOVSKI & ALEKSANDROV, 1995; TASEV, 2003]. The ore veins in the

Zletovo deposit have a general trend of northwest-southeast and belong to the group of single or simple ore veins (Fig. 8).

Only ore veins 13 and 10 have opposite directions of strike and slip, but have the same mineral characteristics as the other ore veins (SERAFIMOVSKI, 1990). The third shape of the ore bodies in the Zletovo mine is the ore pillars or the thickening of the ore veins in their surface parts. These are parts of ore veins with a high concentration of predominantly galena ores, and the lead content is about 0.15% Pb. On average, the thickness of the ore veins ranges from 1 to 3 m, and the salband parts of the veins are mostly kaolinized, silicified and carbonized. Zoning of the basic ore metals in the ore veins going from surface to depth is characteristic. In the superficial parts, lead dominates, followed by a transition with Pb + Zn, then Pb + Zn itself and in the deeper parts Zn + Cu [EFREMOV, 1993; TOMSON et al., 1998]. The mineral association is dominated by galena and sphalerite, followed by chalcopryrite, pyrite, tetrahydrite, tennantite, arsenopyrite, argentite, polybasite. It is regularly associated with quartz, siderite and barite with kaolinite [SERAFIMOVSKI 1990; SERAFIMOVSKI et al., 2006]. The content of lead and zinc and their economic parameters within the Zletovo ore deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) and their summary can be found in Appendix 2; Table 2.

From the genetic point of view Zletovo can be defined as a sub-volcanic hydrothermal vein type ore deposit with Pb-Zn mineralization localized within the volcanic tuff and ignimbrite of andesite and dacite composition. A fluid inclusion study confirmed the hydrothermal character of the ore-bearing fluids dominated by their chloride composition with homogenization temperatures within the range of 335–145°C and salinities from 4.4 to 8.6 wt% eqv. NaCl (TASEV & SERAFIMOVSKI, 2012; TA-

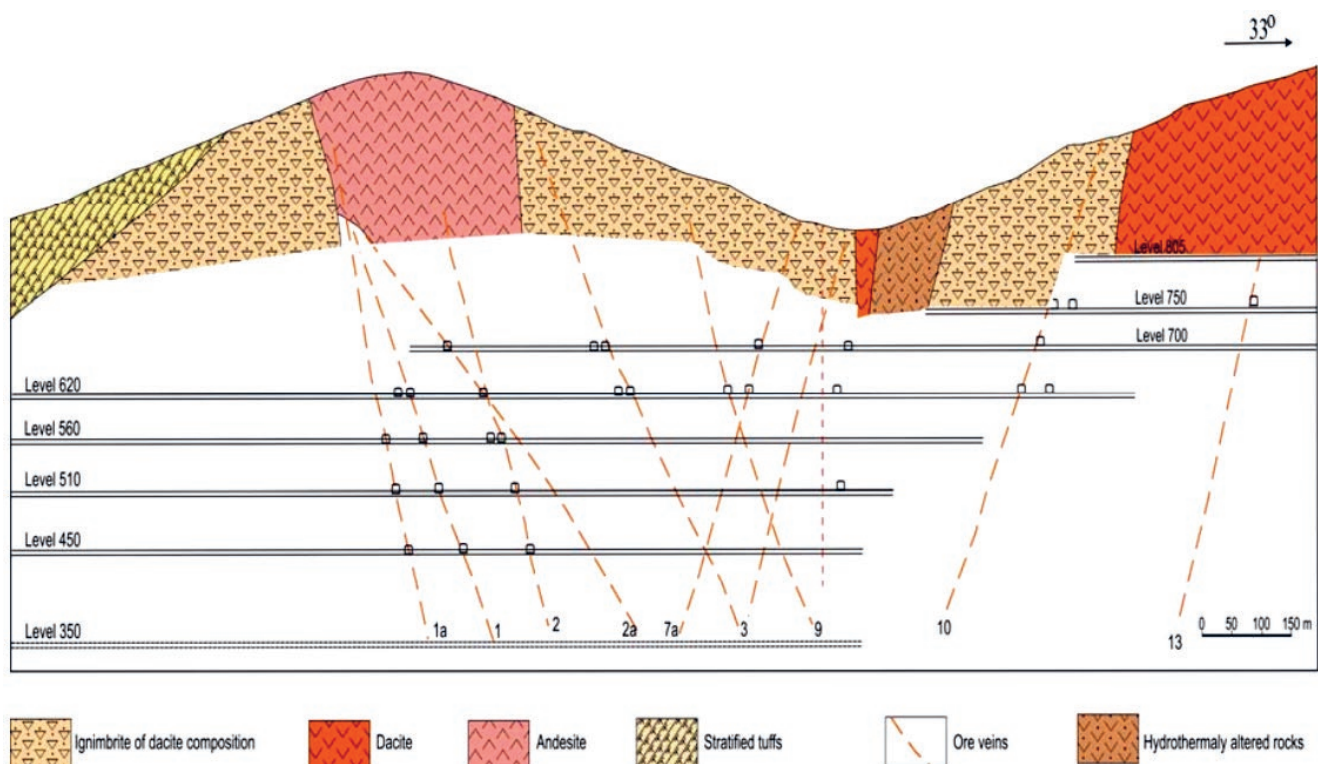


Figure 8. A geological cross section through the Zletovo Mine (after ALEKSANDROV, 1992).

SEV et al., 2019), while within the lower temperature cleopane parageneses, salinity ranged between 10-25 wt% eqv. NaCl. Sulfur isotope composition in galena and sphalerite has an endogenic origin while the carbon isotope composition points to the participation of meteoric waters in ore-bearing fluids (MUDRINIĆ & SERAFIMOVSKI, 1990-91).

### 3.7. Toranica

The lead-zinc ore deposit of Toranica belongs to the group of deposits that were explored in the period between 1974 - 1978, when the mine started active exploitation (BOGOJEVSKI & GASTEOVSKI, 1990). The ore is located in Precambrian metamorphic rocks such as gneiss and quartz-graphite schist, intruded by Tertiary volcanics dated at 32 Ma (TASEV et al., 2005). Productive lead-zinc ore is localized predominantly in quartz graphite schists in the form of elongated pseudolayers and lenses in the so-called hanging wall gneiss (BOGOJEVSKI, 1990; DOBROVOLSKAYA & STANKOVSKI, 1997; STANKOVSKI, 1997). The contact ore bodies between gneiss and quartz latite, as well as between quartz graphite schist and quartz latite, are less significant than the so-called central ore bodies (Fig. 9) localized in quartz graphite schist (SERAFIMOVSKI & ALEKSANDROV, 1995).

The qualitative-quantitative characteristics of the ores in the Toranica deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) as summarised in Appendix 2; Table 2.

Analysis of the mineral compositions, ore textures and structures as well as the chemical properties of the main ore sulfides defines the following mineral parageneses: quartz-pyrrhotite-galena-sphalerite, pyrite-chalcocopyrite-sphalerite, quartz-epidote-sphalerite-galena, quartz-calcite. The slight difference in the parageneses is defined by sulfide predominance. Parageneses of pyrite, sphalerite, galena, quartz, calcite, epidote and actinolite are represented by several generations. The composition of sphalerite is discriminated from early to late parageneses by the percentage of Fe, Mn, Cd, Cu, while galena has a variable composition of Bi, Ag, Se. The rock-forming minerals differ in the percentage of Fe and Mn (SERAFIMOVSKI & TASEV, 2006). Geochemical properties of minerals and their structural relationship indicate the repeated input of ore-forming solutions (SERAFIMOVSKI et al., 2006).

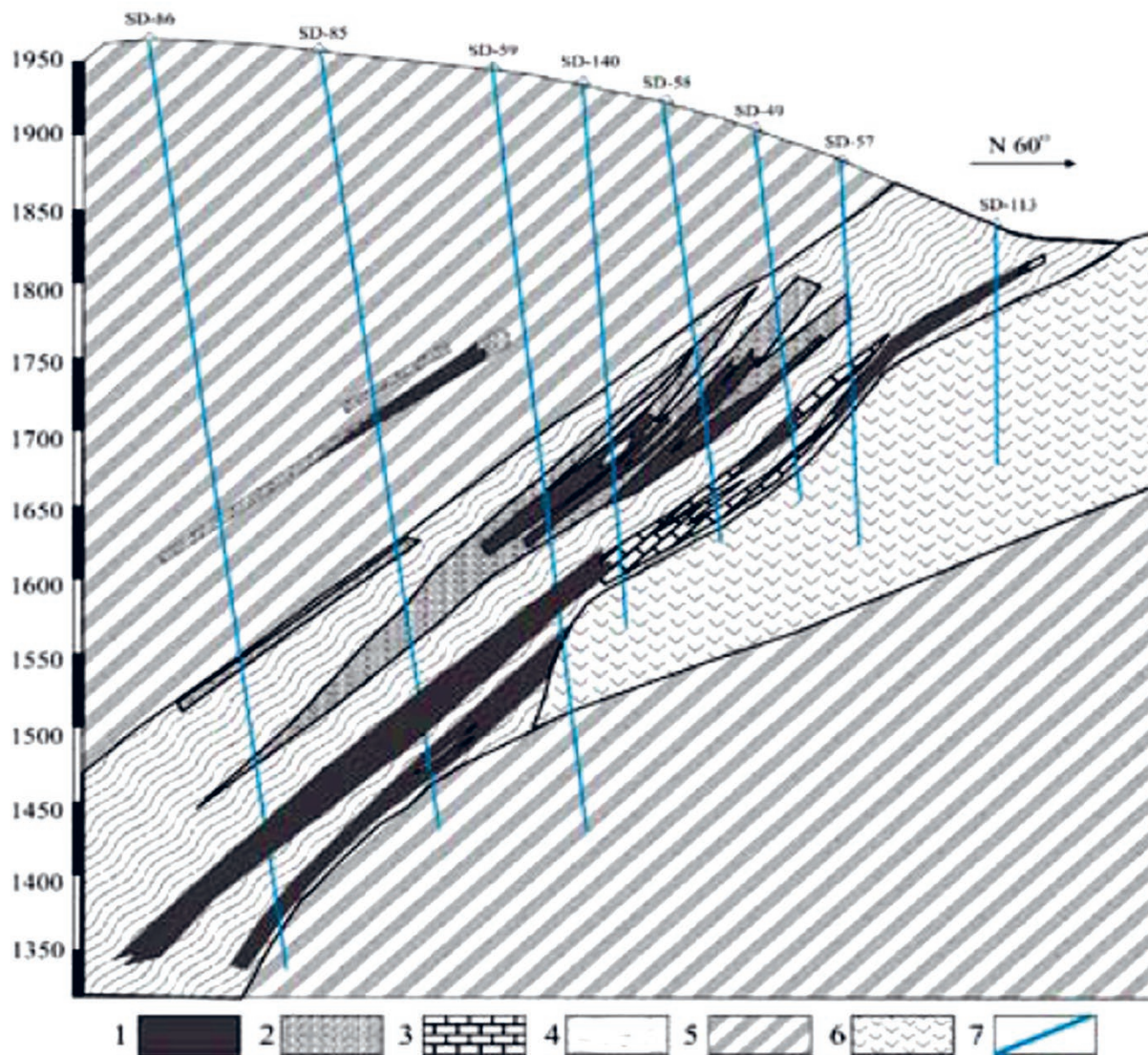


Figure 9. A geological section through the central part of the Toranica ore deposit (after STANKOVSKI, 1997) 1) Ore body, 2) Pb-Zn mineralization, 3) Cipolino marble, 4) Quartz-graphite schist, 5) Gneiss, 6) Quartzlatite, 7) Drill hole.



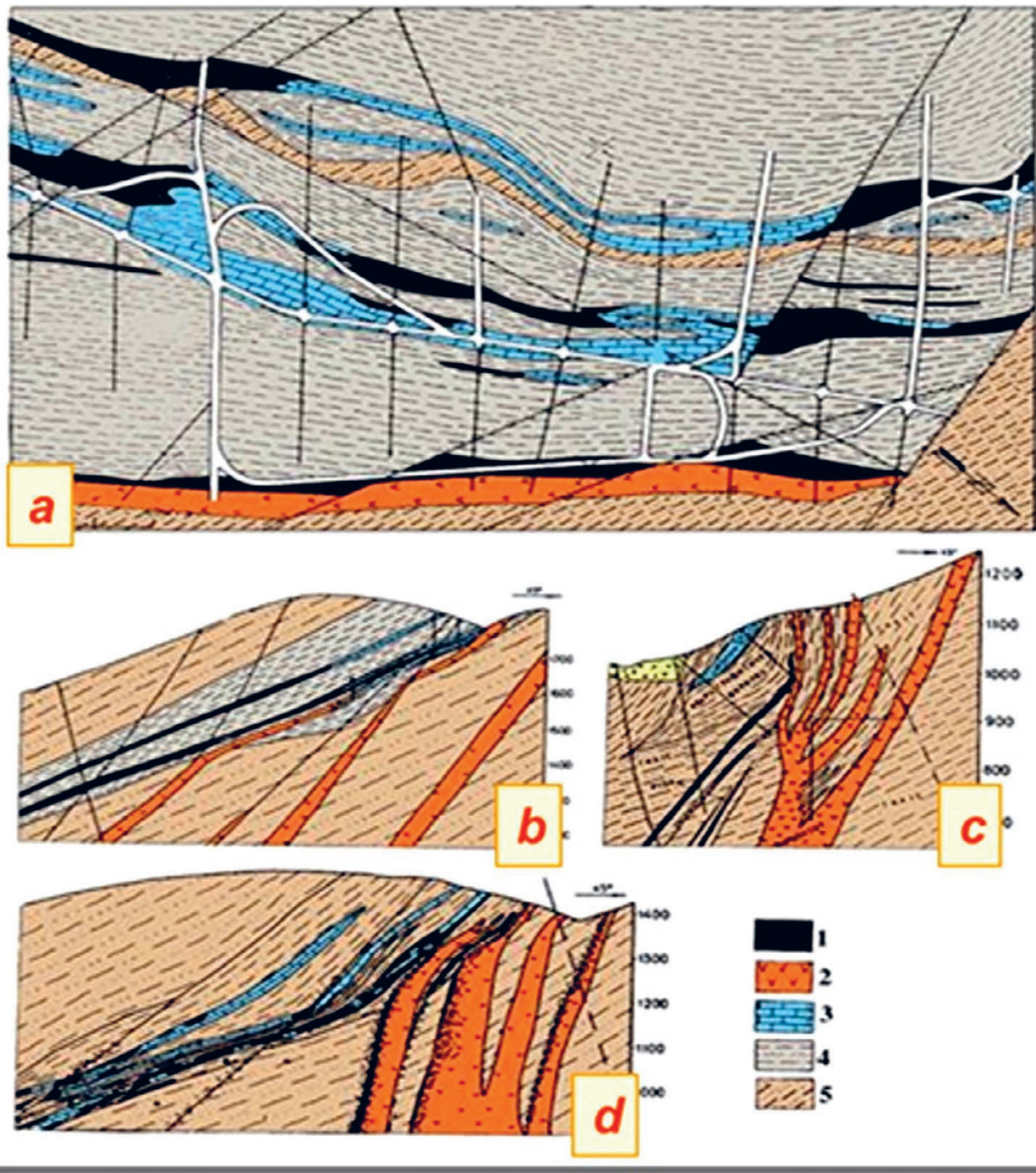
A fluid inclusion study of quartz, calcite and sphalerite, confirmed the hydrothermal character of ore-bearing fluids and the intermittent input of the ore-bearing solutions. The initial stage occurred at 320-370°C and higher salinities (14-16% wt eqv. NaCl; SERAFIMOVSKI et al., 1997), while the later ore-forming stage is characterized by temperatures ranging between 190-250°C and respective lower salinities (4-9 %wt eqv. NaCl). Such numbers indicated later ore forming stages when the ore-bearing capacity decreased significantly.

A study of  $\delta^{34}\text{S}$  in pyrite, sphalerite and galena from the Toranica ore deposit showed a narrow range of variation (+3.15 to 7.54 ‰  $\delta^{34}\text{S}$ , -0.73 to +7.23‰  $\delta^{34}\text{S}$ ) respectively for pyrite,

sphalerite and galena (+0.72 to 5.11‰  $\delta^{34}\text{S}$ ), representing a magmatic origin of the sulfur (SERAFIMOVSKI et al., 1997). A discrepancy of +14‰  $\delta^{34}\text{S}$  (found in pyrite from quartz-graphite schist) was attributed to a sedimentary origin (OHMOTO & RYE, 1979).

### 3.8. Sasa

The Sasa ore deposit, from an economic perspective is the most important lead-zinc deposit in the Republic of North Macedonia, and is listed in the group of several major deposits in Europe. The geological structure of the deposit consists of Precambrian gneiss, Lower Palaeozoic quartz-graphite schist, chlorite-sericite



**Figure 10.** A geological plan and cross section through the Sasa ore deposit (after SERAFIMOVSKI & ALEKSANDROV, 1995). a. Level XV, Kozja River; b. Geological cross section Svinja River; c. Geological cross section Golema River; d. Geological cross section Kozja River; 1. Ore body; 2. Quartz-lattice; 3. Cipoline; 4. Quartz-graphite schist; 5. Gneiss.

schist with intercalation of limestone, calcite schist and quartz-late dykes of Tertiary age (BOGOJEVSKI, 1964; ALEKSANDROV, 1992). Lead-zinc mineralization is localized mainly within the quartz-graphite series with calcite skarn, johansenite and bustamite skarn (Fig. 10). The concentration of lead and zinc in some pseudo-layers and lenses in places is very high and exceeds 20% Pb + Zn, with a silver content of over 50 g/t Ag (SERAFIMOVSKI & ALEKSANDROV, 1995). This productive zone extending from the northwest to the southeast and a southwest dipping slope at depth can be followed for more than 1200 m with an average width of 50 m. The main ore minerals and bearers of lead-zinc mineralization are galena and sphalerite, regularly followed by a lot of pyrrhotite, pyrite and silver-bearing minerals (ALEKSANDROV et al., 1990). Skarn paragenesis consists of garnet, large johansenite, bustamite, ilvaite, epidote and in places calcite and aragonite in the lower parts (SERAFIMOVSKI & ALEKSANDROV, 1995; ALEKSANDROV et al., 1999; STRMIĆ-PALINKAŠ et al., 2013; STRMIĆ-PALINKAŠ et al., 2018)

The qualitative-quantitative characteristics of the ores in the Sasa deposit were prepared in accordance to Selection criteria parameters - Geological criteria, Social licensing, Environmental management, Project permitting, Skills availability (Appendix 1 – Table 1 and Table 2, which were adjusted to the Republic of North Macedonia case) and are summarised in Appendix 2; Table 2.

The origin of lead-zinc ores in the Sasa mine, stratified in the Palaeozoic quartz-graphite schist was interpreted as a syngenetic type TUFAR & STRUCAL (1984). However, BOGOJEVSKI (1964), ALEKSANDROV (1992) defined this deposit as hydrothermal whereas the lead-zinc mineralization is localized in the calcite skarn. This thesis is also supported by STRMIĆ-PALINKAŠ et al., (2018), who also analytically confirms hydrothermal lead-zinc ores within the calcite and bustamite skarn. Our position is based on lead, sulfur, carbon and oxygen isotope analyses data and fluid-inclusions that define the primary origin of ore metals and ore fluids and the hydrothermal character of the deposit.

Most of the analyzed samples indicate the pronounced anomaly of lead isotopic composition (uranogenic or torogenic; SERAFIMOVSKI et al., 1997). The anomaly (18.589-18.700  $^{206}\text{Pb}/^{204}\text{Pb}$ , 15.680-15.827  $^{207}\text{Pb}/^{204}\text{Pb}$  and 38.929-38.990  $^{208}\text{Pb}/^{204}\text{Pb}$ ) could be attributed to contamination by surrounding rocks or due to the redeposition of lead.

Analysis of sulfur in sulfides from the Sasa ore deposit shows narrow ranges of variation. In pyrite values were determined from +4.34 to +6.94‰  $\delta^{34}\text{S}$ , in sphalerite -1.22 to +5.18‰  $\delta^{34}\text{S}$ , in galena from +2.13 to +3.64‰  $\delta^{34}\text{S}$ , pyrrhotite from +1.80 to +3.97‰  $\delta^{34}\text{S}$  and chalcopyrite from +4.39 to +4.41‰  $\delta^{34}\text{S}$ , which together indicates a magmatic origin of S (OHMOTO & RYE, 1979; SERAFIMOVSKI et al., 1997).

The study of the isotopic composition of carbon from the Sasa ore deposit (from -5.50 to -1.48‰  $\delta^{13}\text{C}$ ) indicates its endogenous origin (OHMOTO & RYE, 1979; SERAFIMOVSKI et al., 1997). The  $\delta^{18}\text{O}$  isotopic composition results varied from +16.79 to +23.21‰  $\delta^{18}\text{O}$ , probably indicating the significant fractionation of oxygen from the place of mineral material deposition and its mobilization from carbonates (SERAFIMOVSKI et al., 1997), which is very representative for similar mid to low-temperature hydrothermal ore deposits where meteoric water formed a significant part of hydrothermal solutions (OHMOTO & RYE, 1979).

A study of fluid inclusions in quartz determined primary and secondary fluid inclusions (STRMIĆ PALINKAŠ et al., 2013). Primary fluid inclusions were characterized as two-phase (L+V) inclusions with variable shapes and a degree of fill of 0.75. Temperatures of homogenization vary from 270°C to 300°C while salinities were on the lower end (6.3-7.9 wt% equ NaCl). Post-mineralization minerals analysis, mainly in calcite, proved homogenization temperatures of 125-233°C and even lower salinities, which suggests deposition from colder and relatively diluted ore-bearing fluids.

#### 4. MINING POTENTIAL

As can be seen from published data by the World Mining Data (REICHL & SCHATZ, 2022), the Republic North Macedonia contributes to the World mining of copper, lead and zinc at relatively fair level. Between 2019 and 2020, copper, lead and zinc were officially listed, ranking Republic North Macedonia on position 49 and 47 in regards to copper production, position 15 and 13 in regards to lead production and position 31 in regards to zinc production (REICHL & SCHATZ, 2022). Aforementioned data based on the real geological potential identified for the three commodities, copper, lead and zinc, Republic North Macedonia is capable of performing even at higher level. Here we are discussing, the three indicators of mining potential, grouped by commodity.

##### 4.1. Indicator 1: World Production Ranking

###### 4.1.1. Copper

The World production of copper was 20 788 363 metric tons in 2019, and at the same time, copper production originating from the Republic of North Macedonia reached 6 625 metric tons, which is 0.03% of the total production in 2019. Bearing in mind the reserves and resources of the active copper deposits (mines) within the Republic of North Macedonia and the annual production of 4 to 5 Mt of ore annually, a mine lifetime of more than 20 years looks very realistic. At the present rate of copper production (2019-2020), Macedonia ranks in the lower part of the list (REICHL & SCHATZ 2022), partly due to the fact that in the respective period there was a transition from the production at the Buchim Mine to the newly developed Borov Dol mine.

###### 4.1.2. Lead

With regard to lead, annual production from Macedonia amounts to 44 930 metric tons compared to the 4 747 983 metric tons of World production. This represents 0.95% of world production of lead. Bearing in mind only the reserves of the active lead (and zinc) mines within the Republic of North Macedonia (> 31 Mt of ore) and annual production of 1.5-2 Mt of ore annually, a mine lifetime of more than 15 years looks very realistic, even not considering the resources. At the present rate of lead production (2019-2020), Macedonia ranks in the top 33 % of the World producer rankings list (REICHL & SCHATZ 2022).

###### 4.1.3. Zinc

The World production of zinc reached 12 608 299 metric tons in 2019, and at the same time, zinc production in the Republic of North Macedonia was 31 750 metric tons, (0.25% of total world production in 2019). Due to the fact that zinc is exploited together with lead from the lead-zinc mines (Toronica, Sasa and Zletovo), reserves of more than 31 Mt of lead-zinc ore and an annual production of 1.5-2 Mt of ore should be sufficient for a mine lifetime of more than 15 years (combined). This mine life projection

doesn't consider resources. At the present rate of zinc production (2019-2020), Macedonia ranks in the middle of the World producers ranking list (REICHL & SCHATZ 2022).

#### 4.2. Indicator 2: Self-sufficiency

Recently one of the most vital issues related to the mineral commodities industry became the topic of self-sufficiency. Namely, we cannot ignore the fact regarding the import of necessary mineral commodities. With regard to copper, lead and zinc we would like to emphasize that the Republic of North Macedonia's, according to official statistics (SIMOVSKI, 2020), imports are either very low or absent for these commodities. In contrast, the export of the aforementioned commodities is at significant levels. Before presenting numerical data we would like to stress that due to the proximity of smelting facilities and ports for export, the majority of copper, lead and zinc concentrated production is exported to the neighbouring country of Bulgaria, although certain quantities are coming back to Macedonia due to industry needs. Of a total copper concentrate production of 31 226 metric tons and 28 484 metric tons (in 2019 and 2020, respectively; SIMOVSKI, 2020) around 97-98% was exported. Lead concentrate production amounted to 60 154 metric tons and 62 400 metric tons (in 2019 and 2020, respectively; SIMOVSKI, 2020) of which around 86-97% was exported while in the case of zinc concentrate production (31 254 metric tons and 46 959 metric tons in 2019 and 2020, respectively; SIMOVSKI, 2020) around 49-77% was exported.

#### 4.3. Indicator 3: Economic Contribution

The mining potential of the Republic of North Macedonia can also be expressed through economic parameters. As can be seen in SIMOVSKI (2020), the export of copper, lead and zinc from active mines in the Republic of North Macedonia, expressed in monetary units, reaches 163 256 000 US\$, which compared with the total exports for 2019 of 7 185 157 000 US\$ represents a 2.27% contribution. However, in regards to the economic importance of this industry, the contribution to the Gross domestic product of the Republic of North Macedonia in 2020 of up to 1.8% is more illustrative, while the related industry category that includes mining and quarrying, manufacturing, electricity, gas, steam and air conditioning supply as well as water supply; sewerage, waste management and remediation activities contributed up to 18.1% in 2019 and 17.3% in 2020 of total GDP SIMOVSKI, 2020). Also, here we should take into account the estimated values of reserves/resources of the Kadiica ore deposit, which are up to 369 000 000 US\$ (as of year 2014), the Plavica ore deposit of up to 622 000 000 US\$ (as of year 2014) and the Ilovitsa ore deposit of up to 3 500 000 000 US\$ (as of 2011), which makes an impressive sum of approximately 4.5 billion US \$. In the case of the Kadiica, Plavica and Ilovitsa ore deposits we would like to emphasize that calculations were based on their respective years of calculation of reserves, but since then metal prices have increased substantially, which should increase their values accordingly.

### 5. CONCLUSION

The polymetallic ore deposits (lead, zinc, copper, gold and silver) in the territory of the Republic of North Macedonia are spatially related to the Vardar Zone and the Serbo-Macedonian Massif as the two large geotectonic units of regional scale, and are paragenetically connected to the Tertiary complexes which belong to the metallogenetic zones of Lece-Halkidiki and Besna Kobila-

Osogovo-Thassos, both within the Serbo-Macedonian metallogenetic province.

Two types of lead-zinc deposits have been defined in the Republic of North Macedonia, a typical lead-zinc Zletovo deposit and skarn Pb-Zn deposits at Sasa and Toranica, with the latter having the greater potential. Porphyry copper deposits are located at Plavica, Buchim Borov Dol, Kadiica and Ilovitsa. The most important porphyry copper deposit is at Ilovitsa, which belongs to the Serbo-Macedonian Massif, with proven ore reserves of around 500 Mt. Ore reserves in the Plavica, Buchim and Borov Dol localities are in the order of 100 to 150 Mt, which generally corresponds to the quantities of ore in the porphyry deposits within the Lece-Halkidiki zone, where the Lece deposit in Serbia and the Skouries deposit in Greece have similar features. All of them are located in the contact zones between the Serbo-Macedonian Massif and the Vardar Zone and are a product of calc-alkaline volcanic intrusions that were intruded at sub-volcanic levels. The Kadiica deposit may be promising, but for now only porphyry mineralizations in the oxidation and cementation zones have been defined in that area, while the primary mineralizations need to be further explored.

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## Appendix 1

Table 1: Selection criteria parameters - Geological criteria

Selection criteria 2 (according to Word Risk Report)	RANK (defined by investRM consortium)		
	A	B	C
Parameters (defined by Invest RM consortium)			
Geological criteria	<p>The geological characteristics of the treated polymetallic deposits are fully available through official publications (expert and scientific papers, periodic reports; fund documentation of the companies that have concessions for exploitation or detailed geological research, geological Elaborates for calculation and re-categorization of geological reserves; continuous projects for detailed geological and additional exploration of the deposits, as well as the availability of qualitative and quantitative characteristics of the useful mineral components in the deposit). All geological information on treated polymetallic deposits is public and accessible and very well structured and classified.</p>	<p>High level of availability of geological data and data related to major ore and associated metals for active polymetallic mines of: copper, lead and zinc. Geological data available from professional and scientific papers and scientific publications and operational data available from geological reports that are prepared every 5 years. Annual Metal Production Reports are also a good source of relevant information. Copper deposits (Plavica, Kadlica, Ilovica) that are in the stage of detailed exploration, but are not active have good quality information, at the level of scientific publications and reports, but not at the level of periodic reports and official state data.</p>	<p>In regards of the polymetallic deposits that are in active exploitation (Buchim, Borov Dol, Sasa, Toranica, Zletovo) only certain parts have the character of unexplored potential area (Anishte in the area of Toranica, Crn Vrv-Koshevo in the area of Buchim, Petrova Reka in the area of Sasa, Blizanci in the area of Zletovo) and there the information is mostly old, mainly fund sources and old reports for prospective and in some places detailed geological exploration with drilling, but without updating the data, and the potential is given based on similar criteria from main sites, only, in the polymetallic, mainly copper deposits such as Kadlica and Ilovica, which are still at the level of detailed exploration, the information about the new nearby potential areas is based on modern geophysical research (tellur geophysics) or on the basis of scientific assessment of the potential of the locality-area.</p>
Level of current geological knowledge-quantity	<p>Lead-Zinc: Level A, more than 3.000.000 t of reserves (A+B+C category) and expert judgement. Copper: Level A data quality, more than 10.000.000 t of reserves (A+B+C category).</p>	<p>Lead-Zinc: Level B, less than 2.000.000 t of reserves (A+B+C category) and expert judgement. Copper: Level A data quality, less than 10.000.000 t of reserves (A+B+C category).</p>	<p>Lead-zinc: Any level of data quality, inaccessible documentation, expert judgement-short explanations based on area geological characteristics and historical data. Level C of data quality with inaccessible reserves documentation considering expert judgement.</p>

Table 2: Selection criteria parameters - Social licencing, Environmental management, Project permitting, Skills availability

Selection criteria 2 (according to Word Risk Report)	Parameters (defined by InvestRM consortium)		
	A	B	C
Parameters (defined by Invest RM consortium)			
Social licencing	<p>Acceptance by Local community</p> <p>Excellent, local community is aware of need for economical prosperity that industry brings along, local mines operate without conflict, supported by local community, location of the deposit is within poor rural area in the vicinity of urban area</p>	<p>Sufficient, local community is aware of need for economical prosperity that industry brings along, however several incidents have been recently reported from local mines operate, local community is partly supportive but worried from the aspects of health and safety</p>	<p>Insufficient or problematic based on current state of mining activities; local community does not accept industry due to focus on other area (agriculture, tourism), usually urban area. Local mines experience various problems related to social acceptance.</p>
Environmental management	<p>Legal requirements: Master plan, EIA, Environmental permit</p> <p>Excellent – Environmental permit issued</p>	<p>Good – EIA prepared</p>	<p>Insufficient – exploitation filed NOT included in the Master plan</p>
Project permitting	<p>Legal requirements: Preliminary investigation work, Mining project, Concession permit</p> <p>Excellent – Concession permit issued</p>	<p>Good – mining project approved</p>	<p>Insufficient – no research approved and/or no reserves determined</p>
Skills availability	<p>Labour cost, skills, task force defined in a WP2 Social and Economics data</p> <p>4-5 unique rank for B&amp;H; in general</p>	<p>15% higher than average salaries</p>	

**Appendix 2. Base metals deposits in Republic North Macedonia**

**Table 1.** Cu-polymetallic deposits in the Republic North Macedonia (data compiled after references used in verification and evaluation phase: ČIPLIGANEĆ (1987); TAŠEV (2010); GRAY et al., (2017); FORWARD et al., (2017)); SERAFIMOVSKI et al., (2017).

Area	Deposit	Key to Figure 1	Age	Shape	Mineral	Commodity	Au (g/t)	Cu (%)	Reserves (t) (A+B+C <sub>1</sub> )	Reserves + Resources (t) (A+B+C <sub>1</sub> +C <sub>2</sub> +D)	Data level	Quantity- perspec- tivity	Social licencing	Environ- mental manage- ment	Project permit- ting	
Kratovo- Zletovo	Plavica	1	Oligocene- Miocene	disseminated, stockwork (porphyry style)	Chalcopyrite- enargite-luzonite	Cu-Au-Ag	0.281	0.142	241000000	500,000,000.0	741,000,000.0	A	A	B	C	
Buchim- Damjan- Bunardžik and Cukar Borov Dol		2	Oligocene- Miocene	disseminated, stockwork (porphyry style)	Chalcopyrite-pyrite- cubanite-bornite- native Au	Cu-Au-Ag	0.128-0.129	0.186-0.194	23490000	12,232,000.0	35,722,000.0	A	A+	A	A	
	Borov Dol	3	Oligocene- Miocene	disseminated, stockwork (porphyry style)		Cu-Au	0.128-0.167	0.228-0.256	63845000	18,469,000.0	82,314,000.0	A	A+	A	A	
Ograzden	Ilovlca	4	Oligocene	Porphyry Cu-Au stockwork	Chalcopyrite-pyrite- chalcocite-covellite- bornite	Cu-Au	0.27-0.28	0.184-0.189	458761680	300,000,000.0	758,761,680.0	A	A	C	B	C
Pehcevo- Kadilca	Kadilca	5	Oligocene- Miocene	disseminated, stockwork (porphyry style), main mineral bearing mineralization secondary sulfide enrichment	Chalcocite-covellite- pyrite-chalcopyrite	Cu	-	0.2136- 0.2181	69313134	32,000,000.0	101,313,134.0	A	A	C	B	C

**Table 2:** Lead and zinc deposits in Republic North Macedonia (data compiled after references used in verification and evaluation phase: SERAFIMOVSKI & ALEKSANDROV (1995); STRMIĆ-PALINKAŠ et al., (2013); STRMIĆ-PALINKAŠ et al., (2018))

Area	Deposit	Key to Figure 1	Age	Shape	Mineral	Commodity	Ag (g/t)	Pb+Zn (%)	Reserves (t) (A+B+C <sub>1</sub> )	Reserves + Resources (t) (A+B+C <sub>1</sub> +C <sub>2</sub> +D)	Data level	Quantity- perspectivity	Social licencing	Environmental management	Project permitting
Sasa- Toranica	Sasa	8	Oligocene- Miocene	irregular, vein	Galena-Sphalerite	Pb-Zn-Ag	22	7.5-8.39	18937797	96237797	A	A+	A	A	A
	Toranica	7	Oligocene- Miocene	irregular, bands, layers, lenses	Galena-Sphalerite	Pb-Zn-Ag	20	6.33-7.40	4959101	12600000	A	A+	A	A	A
Kratovo- Zletovo	Zletovo	6	Oligocene- Miocene	irregular, vein, impregnations and stockwork	Galena-Sphalerite	Pb-Zn-Ag	42	7.95-8.01	6958708	8729627	A	A+	A	A	A

