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NEW METALLOGENETIC CONCEPTS AND SUBSTAINABILITY PERSPECTIVES FO NON-ENERGY METALLIC MINERALS IN CENTRAL MACEDONIA, GREECE

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Abstract

Greece's geology favours a potent and dynamic use of mineral resources, which became a major incentive of the country's mining business, and economic and social growth. Among the Non-Energy Metallic Minerals (NEMM) commodities, base and precious metals, in particular copper and gold, is becoming an increasingly important and rapidly growing target of the mining industry. In the region of central Macedonia, where most of their deposits are hosted, the NEMM occur in a wide range of genetic types related to Alpine orogenic and subduction related ore forming processes extending from Mesozoic to Cenozoic times, and culminating during the Tertiary (Arvanitidis and Amov, 2006). From the global metallogenetic point of view the post-Alpine Tertiary geodynamic systems in SE Europe are potential in producing high-grade ore deposits of base and precious metal sulphide minerals. The classification of NEMM mineralizations to specific genetic types, along with the geological knowledge available, is contributing (a) to more efficient exploration and prospect evaluation (b) to safer assessment of ore potential and economic perspectives (c) to rational management of resource production, and (d) in applying sustainable development practices.

1. Introduction

This paper focuses on the NEMM of central Macedonia in northern Greece (Diakakis and Stephanidis, 1994) using new metallogenetic aspects for implementing low-risk exploration campaigns, reducing environmental footprints and securing sustainable supply and use of commodities (Arvanitidis, 2003).

2. Regional Geology and Mineralizations

The sulphide mineral deposits in Greece are mainly located, in the Rhodope and Serbomacedonian zones. The western and central parts of the Rhodope zone consist mainly of Paleozoic high-metamorphic rocks, but its eastern part is dominated by Tertiary volcanics. The Tertiary volcanic belt extends through the northern Mediterranean, Romania, Bulgaria, Greece, Turkey and Iran and is characterized by subduction – related intermediate to felsic volcanics (Jankovic et al., 1980; Heinrich and Neubauer, 2002) (Fig. 1). The belt hosts numerous vein – type (e.g. Kirki, Madjarovo) and stratiform (e.g. Essimi) Pb – Zn sulphide mineralisations as well as epithermal gold (e.g. Konos, Perama; Michael et al., 1995; Voudouris et al., 2007) and porphyry copper deposits (Frei, 1995; Tobey et al., 1998). The highly metamorphosed carbonate and silicate rocks to the west, contain vein and massive sulphide replacement mineralisations, ranging from base metal (e.g. Thermes,

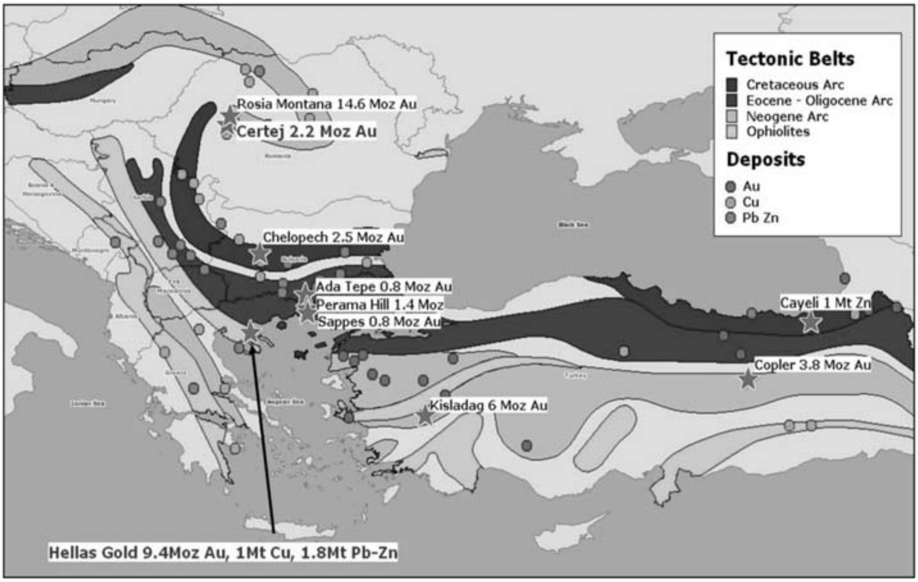

Fig. 1: Regional geotectonic map of southeast Balkan showing the major metallogenetic belts and related mineralization types (European Goldfields Inc, pers. Com.).

Madam) to polymetallic (e.g. Farasino, Pangeo) compositions, and stratabound karst – related Pb – Zn sulphide (e.g. Thassos) to manganese (e.g. Drama) deposits. The Serbomacedonian zone represents the accretionary back land beneath which the African plate was subducted. The zone is a complex metamorphic terrain of schists, gneisses and marbles that are often mineralized and intruded by Variscan granitic rocks. It trends NW, is some 500 km long, and is host to numerous deposits, including Olympias and Stratoni polymetallic deposits, and Skouries and Pontokerasia, porphyry copper in Greece, Sasa and Zletovo Pb – Zn deposits, and Bucim porphyry copper in the Former Yugoslav Republic of Macedonia, as well as the Lece polympetallic deposit in Serbia – Montenegro. In the case of the polymetallic and/or Pb – Zn sulphide replacement deposits such as Olympias, Stratoni and Madem Lakkos, they are controlled by a combination of the marble horizons, that contain the carbonates which were replaced and the deep – seated faults developed as part of the crustal re-working of the area and subsequent fluid movements along these. The porphyries are mainly part of the Variscan volcanism. The Skouries deposit is a typical representative of sub-alkaline copper porphyry forming a near-vertical pipe intruded into amphibolite and biotite schist country rock.

Genetic Types

NEMM mineralization in the region of central Macedonia comprises (Fig. 2).

Mesozoic mid-ocean types in terms of,

- Magmatic/ophiolites hosted chromite, Fe-Ni laterites and chalcopyrite-pyrite-pyrrhotite assemblages
- Volcano-sedimentary syngenetic deposits including VMS type stratiform base metal sulphides, stratified chalcopyrite-pyrite-arsenopyrite lenses, banded iron formations and scheelite (W) veins/disseminations
- Intrusion related porphyry type Mo stockwork veins and impregnations, and

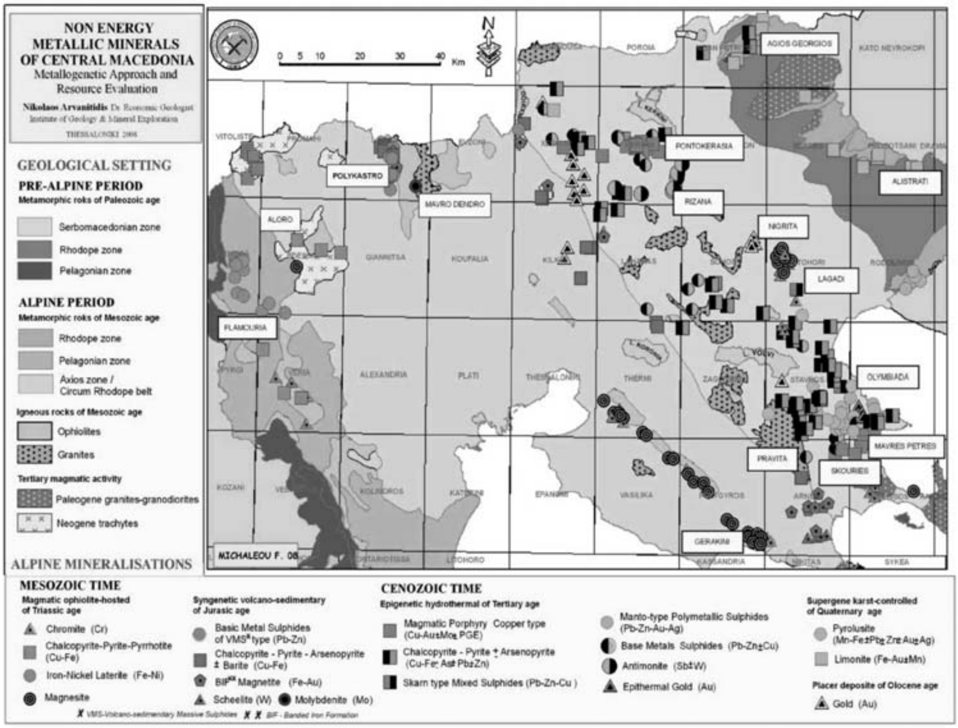

Fig. 2: Simplified geological map showing the main Alpine orogenesis related polymetallic mineralizations in the region of central Macedonia.

Cenozoic, mainly Tertiary, epigenetic, hydrothermal types of,

- Magmatic porphyry Cu-Au deposits containing elevated values of PGE and associated with calc-alkaline sub-volcanic intrusions (Eliopoulos and Economou-Eliopoulos, 1991)
- Hypothermal/Mesothermal chalcopyrite-pyrite-arsenopyrite veins hosted by amphibolites
- Skarn formations of Cu-Zn-Pb sulphides
- Manto type polymetallic (Pb-Zn-Au-Ag) massive sulphides
- Antimonite (Sb) - scheelite (W) veins (Kilias et al., 1995)
- Epithermal gold (Au) along with fault-controlled silicification and pyritization zones
- Supergene fault/karst-controlled mineralization of economic pyrolusitic manganese and gold bearing limonitic iron oxidations
- Placer gold deposits

4. Gold Mineralizations

Gold occurs in a wide range of genetic types, comprising magmatic, hypothermal / mesothermal, epithermal and supergene mineralization types (Arvanitidis, 2003; Melfos et al., 2003). All the main types of gold mineralization are linked to plate tectonic movements during the Tertiary.

Magmatic porphyry copper type deposits and mineralizations show economic gold grades. The Skouries gold-copper ore deposit (Frei, 1995; Tobey et al., 1998) is located 20km southwest of the

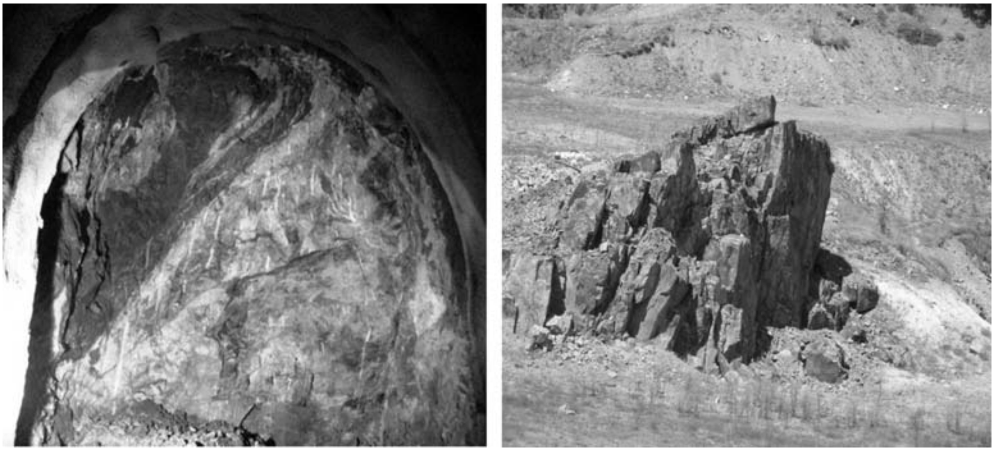

Fig. 3: Typical ore structures of manto-type stratabound sphalerite lens (left) in Mavres Petres mine and malachite impregnations in Skouries porphyry copper mineralization.

Olympias mine and the most representative example of this class (Fig. 3). It is a typical sub – alkaline copper porphyry forming a near – vertical pipe intruded into amphibolite and biotite schist country rock. The deposit is characterized by concentric alteration zones comprising an inner potassic zone, with stock work quartz veinlets and an outer propylitic zone, affecting mostly the host schists. Weak phyllic and argillic alteration is confined to vein haloes and faults. Mineralisations within the potassic zone primarily comprise chalcopyrite veinlets with subordinate bornite and disseminated chalcopyrite and bornite. Mineralisation within the propylitic zone contains disseminated pyrite, molybdenite and rare chalcocite. Gold mineralisation occurs as native gold associated with gangue minerals. It also occurs as blebs within sulphides and occurs in the ore during testing. An oxide zone occurs from surface to 30 to 50 meter depths and includes malachite, cuprite, secondary chalcocite and minor azurite, covellite, digenite and native copper. The total resources were estimated to 191,200,000 tonnes, with 0.82 g/t gold and 0.55 wt% copper, or in terms of total metal amounts, 5.03 Moz gold and 1.043.000 tonnes copper. Current reserves are estimated to 129,500,000 tonnes, with 0.89 g/t gold and 0.56 wt% copper, corresponding to metal amounts of 3.71 Moz gold and 725,000 tonnes copper (Hellas Gold, pers. com.).

Hypothermal / mesothermal manto-type polymetallic sulphides form high - grade gold ores (Kalogeropoulos et. al., 1989; Hellingwerf et. al., 1993; Kalogeropoulos et. al., 1996; Kilias et. al., 1996). The Olympias massive deposit, representing this class, is a stratabound replacement orebody occurring at the contact between marbles and overlying gneisses. Sulphide mineralisations comprises pyrite, arsenopyrite, sphalerite, galena, tetrahedrite – tenantite, boulangerite and chalcopyrite. Gold values are associated almost exclusively with arsenopyrite and pyrite. The total resources and nearly reserves, were estimated to 14,528,000 tonnes, with 9.31 g/t gold, 128.6 g/t silver, 4.18 wt% lead and 5.58 wt% zinc (Hellas Gold S.A., pers. com). Corresponding total amounts of metal contents are 4.35 Moz gold, 60.06 Moz silver, 607,000 tonnes Pb and 810,000 tonnes zinc. Further to the north, the Stratoni lead-zinc-silver deposits are also considered as carbonate replacement type mineralisations, with pyrite, galena, sphalerite, arsenopyrite and chalcopyrite as the main sulphide minerals. The entire resources are currently located in the Mavres Petres mine contained within a marble-hosted stratabound orebody adjacent to the east-west striking Stratoni Fault. The ore is also gold bearing, mostly associated with the arsenical pyrite and arsenopyrite. Quartz, calcite and minor rhodochrosite form the gangue minerals. The total sulphide content prior to mining was estimated at 2.5 Mt (Hellas Gold, pers. com.).

Epithermal type deposits were emplaced within a broad volcanic belt, which developed first in Bulgaria and then moved south through northern Greece (Marchev et al., 2005) to the region of Thrace. The Konos - Sappes and Perama high sulphidation gold mineralizations (Michael et al., 1995; Voudouris et al., 2007; Michael, 2004), in strongly silicified and/or argillised felsic volcanics, make a typical representative of this class. A rhenium-rich molybdenite and rheniite Mo–Cu–Te–Ag–Au porphyry mineralization located in the Pagoni Rachi area shows close geotectonic setting affinities to the epithermal metallogenesis of the region (Voudouris et al., 2009).

The genetic link between porphyry coppers and large polymetallic manto style sulphide deposits can be incorporated into regional exploration strategies. The metallogenetic concept suggests that epithermal mineral assemblages exposed at the present land surface may indicate hidden base metal ore bodies at depth. These styles of mineralization, porphyry coppers and manto - style sulphides, have potential for substantial deposits (Hellingwerf et al., 1994). Gossans in the region have low economic potential due to erratic gold values and the necessity for costly beneficiation techniques (Dimitroula et al., 1995; Arvanitidis et al., 1996). The gossans develop on mineralized veins and thrusts, but the gossanous material tends to spread laterally, giving a false impression of the underlying mineralization. Parts of the gossans can be richer in gold, but these patches mainly constitute small scale exploration targets in west Rhodope.

5. Metallogenetic approach

The tectonic structure of Greece consists of elongated tecto-magmatic strips, representing successive subductions, such as the Serbo-Macedonian massif hosting the manto-type massive sulphide Olympias and Stratoni (Madem Lakkos and Mavres Petres orebodies) deposits, and the porphyry copper systems of Skouries, Fisoka, Vathi, Gerakario and Pontokerasia. The overall metallogenetic process of the area is part of the Alpine orogenesis, lasting from Mesozoic to Tertiary times, and associated geodynamic release of anomalous thermal and mechanical energy. The overwhelming evolution of the Tethyan Ocean, during Triassic to Jurassic times, was accompanied by extensive mid-ocean magmatic activity and new oceanic crust formation, including ophiolitic rocks and related mineralizations (Fig. 4). At a very early transitional stage of subducting oceanic crust movements and distal to mid-ocean ridge settings there were conditions of, probably back-arc, calc-alkaline volcano-sedimentary activity along with formation and deposition of syngenetic metallic minerals of VMS (due to later hydrothermal remobilization may sometimes be considered as “hybrid epithermal VMS”) and BIF types. The progressively collisional subduction and destruction of Tethys led to compressional tensions and mineralized ophiolitic slabs were thrusted over onto Paleozoic continental margin of Serbo-Macedonian basement rocks. The imposed orogenic mechanism and the associated probably post-subduction extensional tectonics (Richards, 2003 and 2009; Marchev et al., 2005) inferred generated intra-continental syn-orogenic faults, formed rift-basins and activated extensive Tertiary magmatic belts of orogenic I-type plutonic and sub-volcanic rocks which during Miocene differentiated partly to back-arc volcanism (e.g. Aridea volcanic belt). The emerging metallogenetic activity of intensive hydrothermal solutions leads to ore formation of manto-type polymetallic sulphides, copper-gold porphyry systems, ISCG–type (Iron Sulphide Copper Gold) gold-bearing pyrite-chalcopyrite -arsenopyrite mineralizations and high sulphidation epithermal gold and Mo–Cu–Te–Ag–Au porphyries along with probably post-subduction extension and rift-basin volcanism further to the east in the region of Thrace (Voudouris et al., 2009). This metallogenetic framework has similar geochemi-

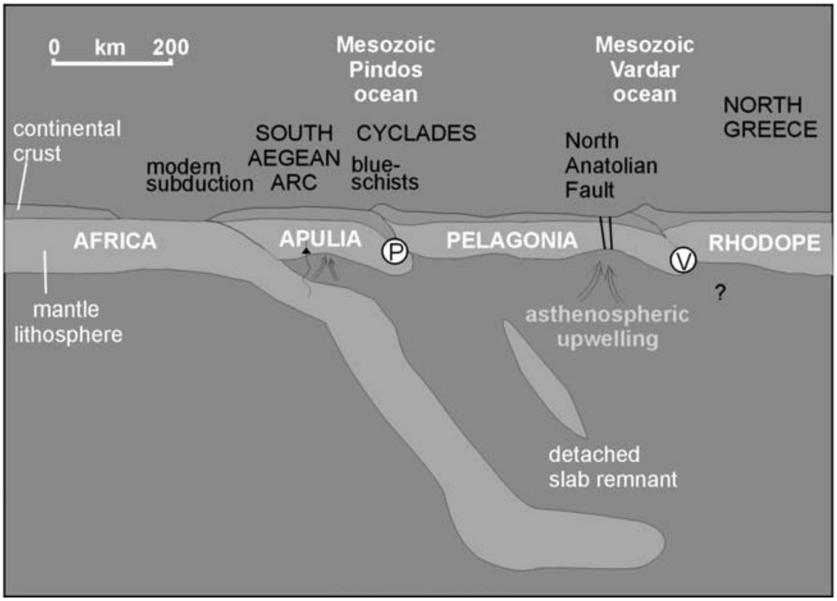

Fig. 4: The main mineralization types in northern Greece and southeast Balkan, and their genetic links to Tethys mid-ocean magmatic activity during Mesozoic and to subduction related orogenic belts during Tertiary (modified after, Pe-Piper, G. and Piper, D.J.W., 2001).

cal affinities with the copper-gold porphyries and the orogenic IOCG (Iron Oxide Copper Gold) type NEMM which at Archean-Proterozoic times are referred to as hybrid porphyry-IOCG style deposits (Weihed et al., 2008). Other typical and common features of the orogenic mineralizations, as the case is for the Tertiary Hellenic mineralizations, are their syn-tectonic and mesothermal characteristics. All previous types of sulphide minerals (particularly those hosted by Rhodope and Serbo-Macedonian marbles) were overimposed by post-Pliocene co-active supergene oxidation and karstification processes (Fig. 5). In spite of the manganese ore formation and the obvious iron enrichment of some occurrences, the metallic content and inter-related commodity grades of the primary sulphide deposits were not particularly affected during supergene oxidation.

6. Implication of new exploration concepts

The metallogenetic regime of orogenic and back-arc magmatic belts is globally one of the most dynamic geotectonic environments for the formation of potential polymetallic, porphyry and epithermal type gold deposits. It has been indicated that almost 50% of porphyry and epithermal type gold occurs in orogenic belts. In this respect, the Alpine or Tethyan orogenic setting makes a high priority target for exploration of Cenozoic NEMM resources and gold deposits in particular. This requires of course further and more systematic ore prospecting of selected regions and areas in Greece and the Balkan Peninsula using new technologies and methods. Based on the geodynamic, spatial and time compliant features of the mineralization types described above, to target and achieve NEMM resource sustainability the following conceptual tools could be applied:

- The local and regional aspects of the metallogenetic evolution which extend the geographical and geological potential of the NEMM resources with respect to transnational targets as for example is the Carpatho-Balkan belt (Jankovic et al., 1980; Heinrich and Neubauer, 2002).

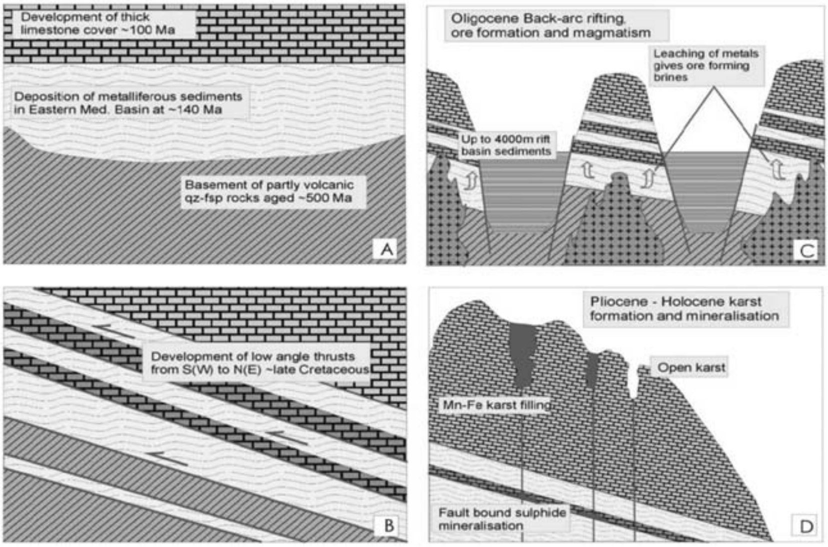

Fig. 5: Schematic integrated four phase mineralization and karst-forming model.

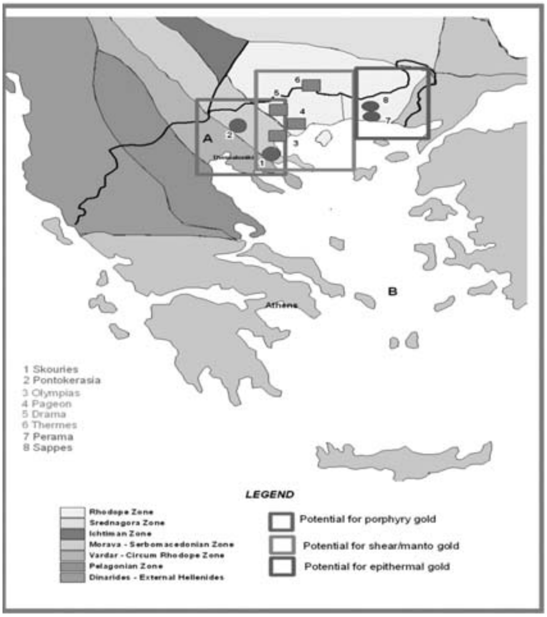

Fig. 6: Major gold potential exploration areas in Greece related to porphyry, manto-type and epithermal mineralization regimes and following the geotectonic and metallogenetic evolution during Cenozoic time.

- The development and implementation of 3D/4D exploration models to locate deep seated mineral deposits in the known manto and porphyry type belts of Serbo-Macedonian zone and the IOCG like supergene assemblages of western Rhodope zone.
- The feasibility studies for the technoeconomical favourable presence of eco-efficient NEMM in the mentioned mineralization types, like for example the promising grades of PGE in the porphyry copper systems, which appear to become critical minerals and hot commodities for the European mining industry.

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