THE GEOLOGICAL SETTING OF BASE METAL MINERALISATION IN THE RHODOPE REGION, NORTHERN HELLAS

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In: J. Boissonal and P. Omenetto (Editors), 1988, *Mineral Deposits within the European Community*. Special Publication No. 6 of the Society for Geology Applied to Mineral Deposits. Springer-Verlag, Berlin, Heidelberg, p.499-514.

Abstract

The Rhodope region of N.E. Hellas is made-up of a complex Lower Palaeozoic (?) basement sequence (metasediments, gneisses and amphibolites) unconformably overlain by Mesozoic and Tertiary formations. There is evidence for ophiolitic sequences in the structurally higher parts of the eastern basement and in the Mesozoic, Circum-Rhodope Belt. Metamorphic grades reach upper-amphibolite facies in the central Rhodope. Base metal mineralisation (Pb, Zn, Cu, Fe, Mn) occurs throughout the region in a variety of environments. Within the basement, sulphides are found associated with marbles (in the west) and amphibolite-serpentinites (in the east). Important base metal occurrences are found in the eastern Tertiary volcano-sedimentary basins, both as strata-bound, syngenetic sulphides and often as fault-controlled Pb-Zn deposits. All of the major deposits, both within the basement and cover sequences, appear to result from a major mineralisation event in the Tertiary. Evidence for this view comes from their homogeneous lead isotope values and the overall mineralisation style, which appears to be controlled by large-scale fracture systems. Field and remotely sensed data provide the basis for a dynamic model in which extensional tectonics, associated with arc magmatism, resulted in hydrothermal solutions migrating through well-defined fracture systems. Isotope data from the major sulphide occurrences support the model of large-scale homogenisation of crustal lead, which was scavenged from the basement and cover sequences. The metals were subsequently dumped in chemically and physically favourable environments, such as marble horizons or into actively depositing basins. Although the region is dominated by Pb-Zn occurrences, there is evidence from the Cu sulphides within the amphibolite-serpentinite sequences that local control did play an important role. Lead isotope data leave no doubt, however, that the mineralising solutions circulated through very large rock volumes outside of the mafic sequences. Overall, the study illustrates the potential of an exploration programme, which uses remotely sensed data in combination with well-constrained ground studies.

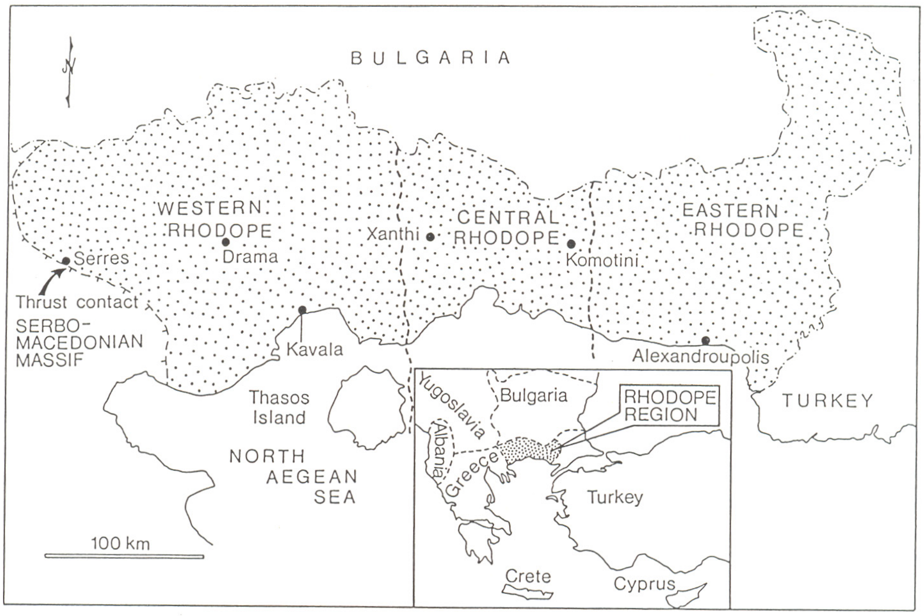

Figure 1. Location of the Rhodope region and its sub-division into the western, central and eastern Rhodope.

1. Introduction

The Rhodope region of Hellas is situated in the north-eastern part of the country and is bordered to the east by Turkey and to the north by Bulgaria (Fig. 1). Geologically, the region can be sub-divided into three units: the metamorphic basement (or basement massif), the Circum-Rhodope Belt and the Tertiary volcanosedimentary basins. The Massif itself extends northwards into Bulgaria and its western boundary is marked by the north-south fracture zone known as the Strimon Fracture Zone. To the west of this zone is the Serbo-Macedonian Massif and together the two metamorphic basement areas form an ancient continental fragment, which was extensively reworked during the Alpine Orogeny. Within the tectonic framework of Hellas, the massifs represent two of the 'internal' geotectonic zones of Marinos (1982).

Mineral exploration and small-scale mining activity for precious and base metals in the Rhodope region dates back to ancient Hellas (Epitropou et al., 1983; Mack, 1983). In recent years the economic potential of the area has increased by the exploration activity of the Hellenic Institute of Geology and Mineral Exploration (I.G.M.E.). Further impetus has been provided by the EC-sponsored programme over the period 1983-1986. This chapter deals with aspects of the general geology with special emphasis on the economic geology of the eastern Rhodope region.

2. Regional Geology

2.1. Metamorphic Basement

The metamorphic basement, which comprises greenschist to amphibolite facies metasedimentary and meta-igneous rocks, can be sub-divided into two major units:

1. the Amphibolite-Gneiss Series consisting of para- and ortho-gneiss, associated with mica schist, amphibolite and thin marble horizons. In the eastern Rhodope, the upper part of this series comprises a 1- to 1.5-km-thick sequence of

metamorphosed mafic and ultramafic rocks, known as the Amphibolite-Serpentinite Unit, and

2. the Carbonate Series, consisting of marble intercalated with mica schist, chlorite schist and quartzite.

The geology of the western Rhodope is dominated by the Carbonate Series (Fig. 2) and estimates of thickness vary from about 1.5 km (Zachos and Dimadis, 1983) down to 300 m (Papanikolaou, 1986). The Series stratigraphically overlies the Amphibolite-Gneiss Series, but tectonic repetition and folding makes detailed correlation difficult. The central and eastern Rhodope are dominated by the Amphibolite-Gneiss Series and in the central region this unit is associated with minor carbonate horizons and isolated occurrences of mafic and ultramafic rocks. In the eastern region, the upper part of the Amphibolite-Gneiss Series is made-up of an Amphibolite-Serpentinite Unit, which consists of metamorphised mafic and ultramafic rocks, which in part is extensively migmatised. This unit has been thrust from the south-east onto the gneissic basement, and may represent part of a disrupted ophiolite complex. Other occurrences of serpentinised ultramafic rocks are found within the Amphibolite-Gneiss Series, particularly in the northern part of the eastern Rhodope.

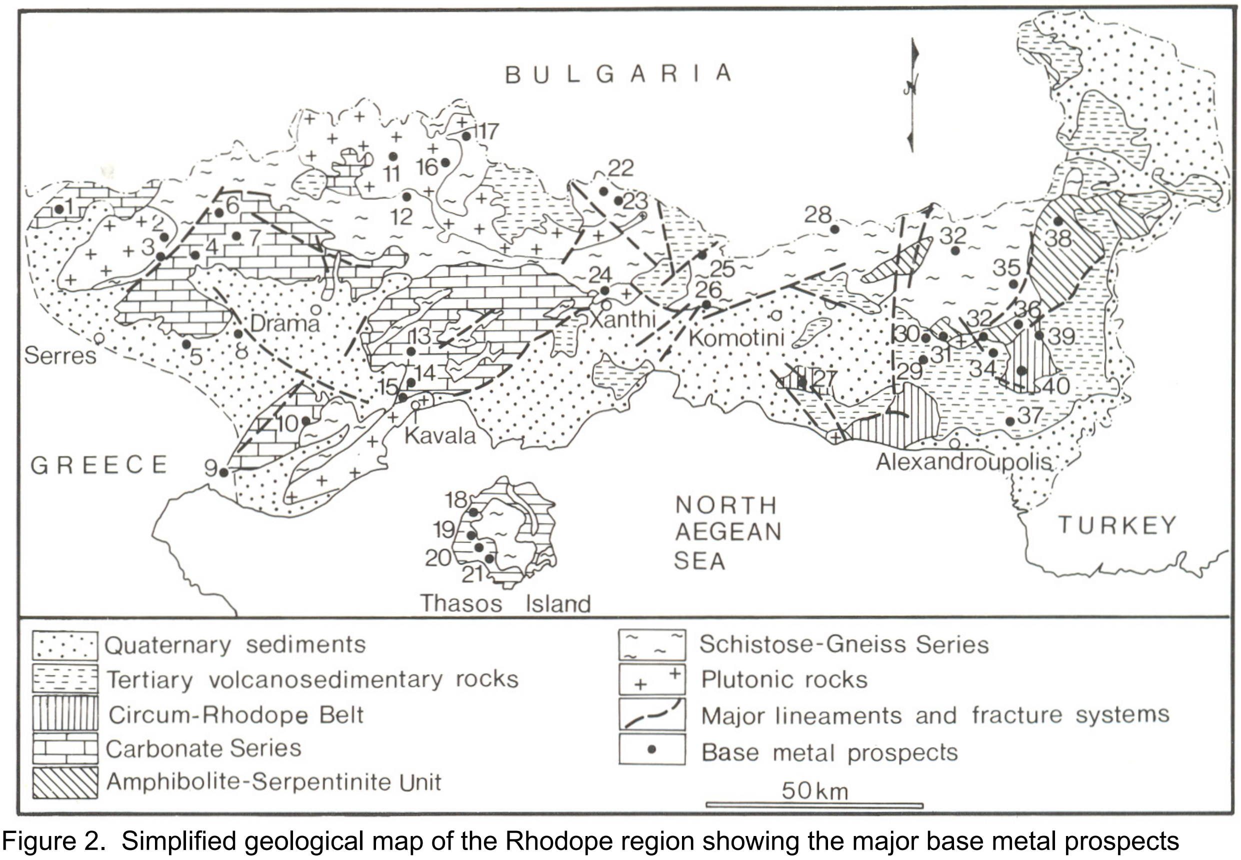

Figure 2. Simplified geological map of the Rhodope region showing the major base metal prospects (after Bitzios et al., 1981). Each prospect is numbered and described in more detail in Table 1.

Overall, the geology of the metamorphic basement exhibits a number of strong contrasts from west to east. In particular, there is a significant decrease in the importance of marble and an increase in the volume of mafic rocks. The significance of this contrast is not fully understood and the lack of a firm geochronology further hampers a better understanding of tectonic and stratigraphic relations. The paucity of firm geochronological data has led Bulgarian geologists to use lithostratigraphic comparisons with other basement terrains, and they have assigned a Proterozoic or an

Archaean age to the Massif (Dimitrov and Zidarov, 1969). Moorbath and Zagorcev (1983) reported a Rb/Sr age of 342 ± 27 Ma for a granitoid complex, which intrudes the basement of southern Bulgaria. This implies that the Rhodope Massif must be of Lower Carboniferous age or older.

2.2. Circum-Rhodope Belt

The Mesozoic Circum-Rhodope Belt formations of the south-eastern margin of the Rhodope Massif exhibit stratigraphic similarities with the Mesozoic volcanosedimentary formations of the innermost orogenic zone of the Hellinides in the Chalkidiki peninsula (Dixon and Dimitriadis, 1984). Katirtzoglou (1986) in the most recent study of the Circum-Rhodope Belt describes the metamorphic basement as being unconformably overlain by a series of phyllites, greenschists, calcareous schists, marbles and volcano-sedimentary rocks. He further sub-divides the sequence into the Makri Unit, comprising carbonates and calcareous schists, which is progressively overlain by the Greenschist Unit and finally by the Drimou Melia Unit. The Greenschist Unit comprises submarine metavolcanic rocks, which may have ophiolitic affinities, whilst the Drimou Melia Unit begins with mafic volcanism and progresses into a sedimentary sequence. The sediments begin with black phyllitic shales and cherts, which pass upwards to a sandstone-quartzite sequence.

The exact age of the Circum-Rhodope Belt is somewhat uncertain. Estimates for the Makri Unit range from Permo-Triassic (Maratos and Andronopoulos, 1964) to early Cretaceous (Katirtzoglou, 1986), whilst the Drimou Melia Unit is thought to be Upper Cretaceous to Palaeogene (Bitzios et al., 1981).

Chemical data on the volcanics (Katirtzoglou, 1986) indicate an initial low-K tholeiite sequence which gradually changed to one of calc-alkaline character. Various writers (e.g., Jacobshagen et al., 1978) have suggested that the Circum-Rhodope Belt contains elements with ophiolite characteristics, and this, combined with the nature of the volcanics, has led to models involving the development of island arcs and subduction-related volcanism. In these models, the Belt is folded, metamorphosed and thrust onto the Rhodope Massif during the late Cretaceous.

2.3 Tertiary Volcano-Sedimentary Basins

The Tertiary volcano-sedimentary basins occur along the southern and eastern margins of the Rhodope Massif (Fig. 2). The basins were initiated during mid-Eocene (Papadopoulos, 1980) and rest unconformably and have tectonic contacts with both the metamorphic basement and the Circum-Rhodope Belt. Initial sedimentation (basal conglomerate, marl and limestones) was followed in the Upper Eocene and Oligocene by a mixed volcano-sedimentary sequence consisting of calcareous sandstones, shales, andesites and rhyolites. The volcanics, which are dominantly of calc-alkaline affinity (Fytikas et al., 1984; Papavassiliou and Sideris, 1984), form part of a major volcanic province in the north Aegean, which is associated with a series of sub-volcanic intrusive rocks of intermediate composition. These form an important component in the development of base metal mineralisation, a subject that is discussed in a later section. Overlying the older formations throughout the Rhodope are a series of Neogene and Quaternary sediments, which include both marine and terrestrial clastic sediments. These do not form part of the present study.

3. Metamorphism and Tectonism

The metamorphic rocks of the Rhodope region have been affected by various degrees of regional metamorphism and deformation. The complex tectonic history of the basement is manifest as a penetrative regional schistosity and a series of isoclinal to open fold structures. Papanikolaou and Panagopoulos (1981) and Papanikolaou (1986) describe three phases of deformation in the western Rhodope with the syntectonic second phase being the most important. The general model is one of a multi phase, recumbent isoclinal folding with associated thrusting - a model also supported by Bulgarian workers (Ivanov et al., 1979). The important conclusion by both Hellene and Bulgarian geologists is that the major deformation is Tertiary in age, with post-Cretaceous nappes recorded by Ivanov (1985) on the northern margin of the Rhodope.

In contrast, the Lower Tertiary volcano-sedimentary sequence is relatively undeformed. Folding, however, does occur locally along the margins of the sedimentary basins (Billett and Nesbitt, 1986) and this is thought to be related to a basin closure in the Oligocene.

The basement rocks of the Rhodope Massif exhibit a number of different metamorphic facies. Recent work on central Rhodope to the east of Xanthi by Mposkos (1986) has demonstrated the presence of several metamorphic zones ranging up to upper amphibolite facies. In the central zone (to the north of Komatini), the grade of metamorphism increases progressively to the NW and Mposkos (1986) has mapped the isograd separating the staurolite-kyanite zone from the kyanite-sillimanite zone. This upper amphibolite facies unit is confined to the migmatite zone, which surrounds the Oraeo-Echinos granite. Further to the east, the eastern Rhodope is thrust onto the central Rhodope Block along the NE-SW trending Kimi-Pandrosos thrust (Mposkos 1986). To the east of the thrust, metamorphic grade is generally of lower to middle amphibolite facies with the highest metamorphic grade (kyanite) being found in the Smiyadi-Kimi Formation immediately east of the thrust. To the east of the thrust, the leucocratic biotite gneisses, which occupy much of the eastern zone of the block, are sub-divided by Mposkos (1986) into a staurolite-chloritoid zone (to the north-west) and a garnet zone (to the south-east). The eastern Rhodope, therefore, shows an increase in metamorphic grade from south-east to north-west. The distinctive Amphibolite-Serpentinite Unit in the extreme east of the Rhodope displays assemblages of actinolite-epidote-oligoclase within the amphibolitic members.

Retrograde metamorphism occurs throughout the Rhodope Massif and is characterised by greenschist facies conditions. This period of metamorphism is thought to be related to a regional metamorphism in the Mesozoic Circum-Rhodope Belt (Mposkos 1986). The major period of regional metamorphism in the crystalline basement must, therefore, be pre-Alpidic.

In several areas in the region, the major metamorphic formations are separated by thrusting. For example, the eastern Rhodope Massif is thrust onto the central Rhodope Massif to the ENE of Komotini (Fig. 2). Although major thrust movements in the Rhodope region are thought to be associated with the collision of the northern European plate with the African plate in the Upper Cretaceous (Robertson and Dixon, 1984), it is most likely that they may represent reactivated basement structures (Zachos and Dimadis, 1986).

This pre-existing structural control may also be true for many of the high angle normal and reverse faults, which are found throughout the region. Recent work by Sanderson et al. (1986) has shown that these faults, not only control the development of the Tertiary volcano-sedimentary basin, but are also important structures for the localisation of the mineralisation. The thrust of Sanderson's argument is that the eastern Rhodope can be considered as lying at the dilational (extensional) termination of the right-lateral North Anatolian Fault system, and that this influenced the development of the Eocene-Oligocene basins. Based on remotely sensed data and ground observations, Sanderson et al. (1986) conclude that the Tertiary basins are bounded by major faults even though this may be masked at the surface by the overlap of sedimentary fill. Thus, the Kirki-Essimi Basin formed as a consequence of a pull-apart at the southern edge of the basement massif as it was extended in a NE-SW direction along a right-lateral 060^{o} trending fault. An interplay between these north-east fractures, and the associated south-east extensional trending faults, produced the zigzag outline of the southern margin of the basin with its general east-west trend. The significance of these fracture systems to controls of known mineralisation is discussed in the following sections.

4. Mineralisation

In this section, we attempt to summarise the main features of the mineralisation in the Rhodope region, by considering in turn the metamorphic basement, the Circum-Rhodope Belt and the Tertiary volcano-sedimentary basins. The main polymetallic prospects in the Rhodope region are located in Figure 2 and listed and described in more detail in Table 1. Many of these prospects are located on the metallogenic map of Hellas published by Zachos and Maratos (1965). However, this new listing contains additional evidence from several old prospects and also a number of new, recently discovered prospects.

4.1 Metamorphic Basement

Approximately 80% of the major base metal prospects in the Rhodope region occur in the metamorphic basement. Within this group three main types of mineralisation are recognised:

1. Vein-type mineralisation associated with faults;
2. Carbonate-hosted mineralisation; and
3. Mineralisation associated with serpentinite and amphibolite.

1. *Vein-type mineralisation*, related to fracture systems, occurs in metamorphic rocks of different composition. In the Tris Vrises area, for example (Prospect No. 35) base metal mineralisation occurs in 0.1-1-m-thick veins in leucocratic gneiss, whereas at Thermae (No. 23) mineralisation occurs in fractures cross-cutting amphibolite and marble. Metasomatic mineralisation occurs at Thermae where faults cut marbles. Wall rock alteration is generally present and pyritic, silicic, chloritic, carbonate and sericitic alteration zones can be recognised in the vicinity of the fractures. The Pb-Zn-Cu mineralisation of the Thermae area is similar to the economic ore deposits of the Madan area in southern Bulgaria (Bogdanov, 1982). Ore concentrations at Madan are controlled mainly by NNW trending faults and mineralisation occurs where faults cross-cut marbles. Throughout the Hellenic Rhodope Massif mineralisation is generally confined to fault systems with a similar north-west to south-east orientation.

2. *Carbonate-hosted base metal sulphide mineralisation* is an important feature in the metamorphic basement. On Thasos Island (Fig. 2) four major Zn (Pb, Fe) sulphide prospects are situated at or close to the contact between the Amphibolite-Gneiss Series and the Kastro Marble Series (Fig. 3). Many of these base metal occurrences are lenticular in form with a limited vertical, but a considerable lateral extent. The deposits appear to be both strata-bound and stratiform in character. The mineralisation is typically karstic, formed by groundwater circulation (Epitropou et al., 1983; Omenetto, 1983). Similar mineralisation occurs in the Palia Kavala area (Prospect No. 12, 13, 14, 15) and in the western Rhodope, Mn (Fe) and Pb/Zn mineralisation occurs at a similar stratigraphic position (Prospect No. 6, 7, 11).

Marble is also associated with classic skarn-type mineralisation related to intrusive granitic rocks. A typical example of this type of mineralisation occurs at the Kimmeria deposit (No. 24), where magnetite-sphalerite-chalcopyrite-pyrite-gold is associated with molybdenite and scheelite. Several other base metal prospects in the western Rhodope have a similar style of mineralisation, namely Vrontou (No. 3), Panorama (No. 4), Ofrinio (No. 9) and Asimotripes Pangaeo (No. 10).

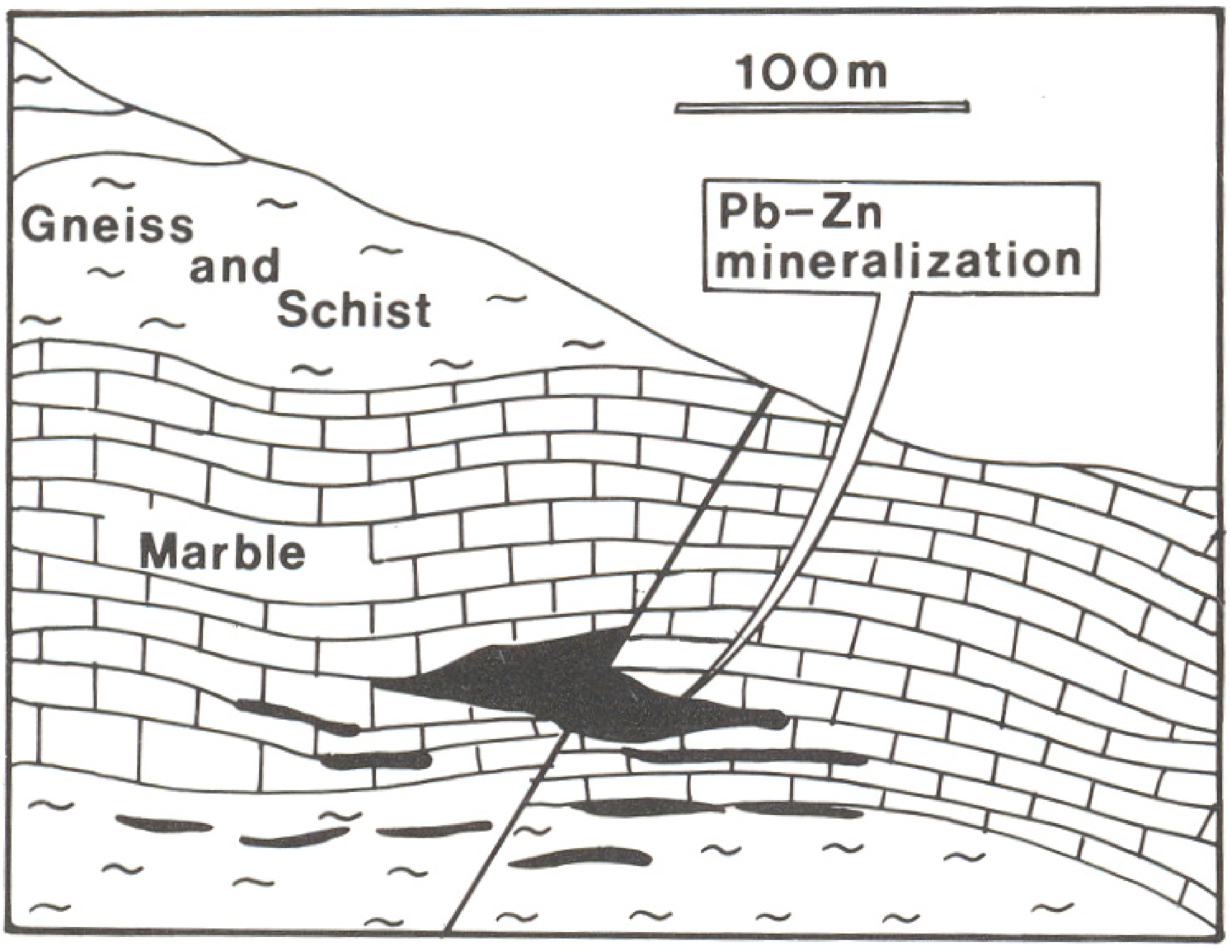

Figure 3. Schematic cross-section of the Marlou PbjZn, prospect No. 19, on Thasos Island (Epitropou et al., 1983).

Table 1. Important base metal prospects in the Rhodope region

Number/name	***Mineralisation***	***Host rock***[a]	***Style/control***
1 Angistro	Zn, Pb, As, (Cu,py,Ag,Au)	Marble/Gn-Sch	Strata-bound
2 Kato Vrontou	py, (Cu,Zn)	Granite	Vein-type
3 Vrontou	py, As,(Pb,Cu)	Marble	Skarn
4 Panorama	Fe, py, (Pb,Zn,W)	Marble	Skarn
5 Dafhoudi	Pb, py, (Cu,Au)	Marble/Gn-Sch	Strata-bound
6 Kato Nevrokopi	Fe,(Pb,Zn,Cu)	Marble/Gn-Sch	Strata-bound
7 Granitis	Mn,(Pb,Zn,py)	Marble/Gn-Sch	Strata-bound
8 Kalithea	Fe,(Pb)	Seds	Strata-bound
9 Ofrinio	py, As, (Pb,Zn)	Marble	Skarn
10 Asimo. Pangaeo	py, As, (Pb,Zn,Au,Ag)	Marble	Skarn
11 Finterna	Mn,(Pb,py,Zn)	Marble/Gn-Sch	Strata-bound
12 Radista	Pb, Zn, Mn, (py,Cu)	Marble/Gn-Sch	Strata-bound
13 Kouroutgou	Zn, Fe,(Pb,Cu)	Marble/Gn-Sch	Strata-bound
14 Mandra Kari	Fe, Mn, (Pb,Zn)	Marble/Gn-Sch	Strata-bound
15 Amigdaleon	Fe, Mn,(Pb,Zn)	Marble/Gn-Sch	Strata-bound
16 Pefki	Pb, Zn, py	Marble	Vein-type
17 Farasino	Pb, py,(Zn,Cu)	Marble	Vein-type
18 Sotiras	Zn, Pb, (Fe)	Marble/Gn-Sch	Strata-bound
19 Marlou	Pb, Zn, (py)	Marble/Gn	Strata-bound
20 Koumaria	Zn, (Pb, Fe)	Marble/Gn	Strata-bound
21 Vouves	Zn, (Pb, Fe)	Marble/Gn	Strata-bound
22 Diasparto	Pb, Zn, py, (Cu)	Marble/Gn-Sch	Fracture
23 Thermae	Pb,Zn, py, (Cu,Ag)	Marble/Gn-Amp	Fracture
24 Kimmeria	Fe, Zn, Cu, py, (Pb,Mo,W)	Marble	Skarn
25 Kaloticho	py, Pb, (Cu,Zn)	Gn-Sch	Vein-type
26 Iasmos	py, Pb, (Cu,Zn)	Gn-Sch	Vein-type
27 Xilayani	py, (Cu,Zn,Au)	Greenschist	Strata-bound
28 Sarakini	py, Cu, (Pb,Zn)	Basic Gn	Vein-type
29 St. Philip	Zn, Pb, py (Cu,Ag)	Seds	Fracture
30 King Arthur	py, Zn, Cu, Pb	Voles	Vein-type
31 Aberdeen	py, Cu(Zn,Pb)	Amph Serp	Fracture
32 Kechros	Zn, Cu, py, Pb	Acid Gn	Vein-type
33 Baiko (1)	Fe, (Cu,py)	Marble/Amp	Strata-bound
Baiko (2)	py, Cu, (Zn,Pb)	Amp/Serp	Various
34 Essimi (1)	py, Zn	Amp	Stratiform
Essimi (2)	py, Zn, Pb, (Cu,Ag)	Seds/Volcs	Stratiform
Essimi (3)	py, Zn, Pb, Cu	Seds	Vein-type
Essimi (4)	py, Cu	Intrusives	Porphyry
35 Tris Vrises	Zn, Pb, py, Cu	Acid Gn	Fracture
36 Pessani	py, Cu (Pb)	Amp/Serp	Stratiform
37 Pefka	Cu, py, Pb, (Zn,Sb,Ag,Au)	Voles	Vein-type
38 Mikro Dherio	py,(Cu)	Greenschists	Strata-bound
39 Virini	py, Zn, Pb, Cu	Seds/Volcs	Vein-type
40 Elva	py, Cu	Greenschists	Strata-bound

[a] Gn = gneiss; Sch = schist; Seds = sediments; Amp = amphibolite; Serp = serpentinite; Volcs = volcanics

3. *Mineralisation related to serpentinites and amphibolites* occurs in a sequence of metamorphosed mafic and ultramafic rocks in the eastern Rhodope, known as the Amphibolite-Serpentinite Unit. Recent research work in the eastern Rhodope has concentrated on investigating the geological controls of this type of mineralisation. Current ideas on its origin are discussed in Billett and Nesbitt (1986). Three major prospects occur in the Amphibolite-Serpentinite Unit: Aberdeen (No. 31), Baiko (No. 33) and Pessani (No. 36). A fourth prospect (Essimi, No. 34) has only been intersected by drilling. The mineralisation is predominantly Cu-rich in contrast to the Zn- and Pb-rich mineralisation of other parts of the Amphibolite-Gneiss Series and the Carbonate Series.

In the Baiko area (No. 33) of eastern Rhodope two types of mineralisation occur. Strata-bound magnetite-pyrite-chalcopyrite mineralisation occurs within a 40-50-m-thick sequence of intercalated amphibolite, marble and granitic bands. The mineralisation, which extends for at least 1 km along the strike, is concentrated in metasomatic, epidote-rich areas at the contact between mafic and carbonate bands (Billett and Nesbitt, 1986). The second type of mineralisation is amphibolite-hosted and consists of pyrite-chalcopyrite mineralisation, which is spatially related to the interplay of a major isoclinal fold with a Tertiary felsic intrusive body. Within the tectono-stratigraphy of the Amphibolite-Serpentinite Unit, the pyrite-chalcopyrite mineralisation lies at the contact between a unit of serpentinite and a unit of mafic amphibolite. The second type of mineralisation at Baiko is, therefore, fundamentally different from the strata-bound magnetite-pyrite-chalcopyrite mineralisation.

The Aberdeen prospect lies on a north-south trending fracture zone close to an intersection with an east-west trending fracture. The mineralisation, which comprises chalcopyrite-pyrite ± magnetite, occurs in the lower part of a unit of serpentinites cross-cut by felsic pegmatites, close to its contact with an underlying unit of mafic amphibolite. The mineralised zone varies in width from 3-7 m and extends for 300-350 m in a north-south direction.

Mineralisation at both Aberdeen and Baiko occurs at or close to the lithological boundary between serpentinites and mafic amphibolites. Petrochemical studies of both these units show that they comprise a comagmatic suite of mafic and ultramafic rocks (Billett and Nesbitt, 1986). The presence of relict textures in the rocks, such as rhythmic layering, ophitic and pegmatitic textures, show that the mafic amphibolites represent a metagabbroic sequence. Their geochemistry, although variable, is comparable to intrusive gabbroic rather than extrusive basaltic rocks. The Cu-Fe sulphide occurrences at Aberdeen and Baiko are, therefore, associated with metamorphosed mafic and ultramafic rocks, rather than the more widely recognised association of base metal mineralisation with mafic volcanic rocks.

Pessani, the third major prospect in the Amphibolite-Serpentinite Unit, occurs in minor fractures along a similar contact between mafic and ultramafic rocks. Mineralisation comprises supergene and primary Cu and Fe oxides and sulphides with minor galena. The concentration of base metals along this contact is also shown by soil geochemical traverses across the area (Michael et al., 1984). The geochemical anomalies show that the amphibolite is preferentially enriched in base metals in the immediate vicinity of serpentinite bodies. Billett and Nesbitt (1986) suggest that fluids related to serpentinisation have mobilised base metal sulphides in the surrounding amphibolite and produced metal concentrations at the margins of serpentinite bodies. Fluid flow and mineralisation may also be enhanced by the relatively ductile contact between serpentinite and amphibolite.

In the Amphibolite-Serpentinite Unit the occurrence of a Cu-dominated base metal mineralisation is directly related to the nature of the host rocks. The formation of sub-economic mineral prospects is a result of secondary processes, such as fracturing (Aberdeen and Pessani), folding (Baiko) and igneous intrusion (Baiko), which resulted in the concentration of base metals from low background levels in the mafic and ultramafic rocks. The fluids which effected this concentration of base metal sulphides, either originated from the serpentinites themselves or from the passage of hydrothermal fluids along the lithological contact between amphibolites and serpentinites. Economou and Naldrett (1984) have proposed a similar model for the formation of Cu-Fe sulphide halos that occur at the peripheries of podiform chromite bodies in serpentinites. They suggest that base metals precipitated from hydrothermal fluids which also caused serpentinisation of the host rocks.

4.2 Circum-Rhodope Belt

The Circum-Rhodope Belt is found only in the eastern Rhodope region, where it is associated with a number of prospects. The Xilayani prospect (No. 27), which comprises disseminated and massive pyrite with minor chalcopyrite and rare sphalerite and galena, occurs in a unit of low grade metamafic rocks (Bitzios et al., 1981). The ore is lenticular in form and coplanar to the regional metamorphic fabric (Fig. 4). It is, therefore, considered to be a syngenetic, stratiform, volcanogenic deposit of Cyprus-type (Bitzios et al., 1981; Constantinides et al., 1983). A similar type of mineralisation occurs in the Mikro Dherio area (prospect No. 38), where disseminated pyrite and minor chalcopyrite are associated with sub-greenschist facies metatuff and metamafic lava.

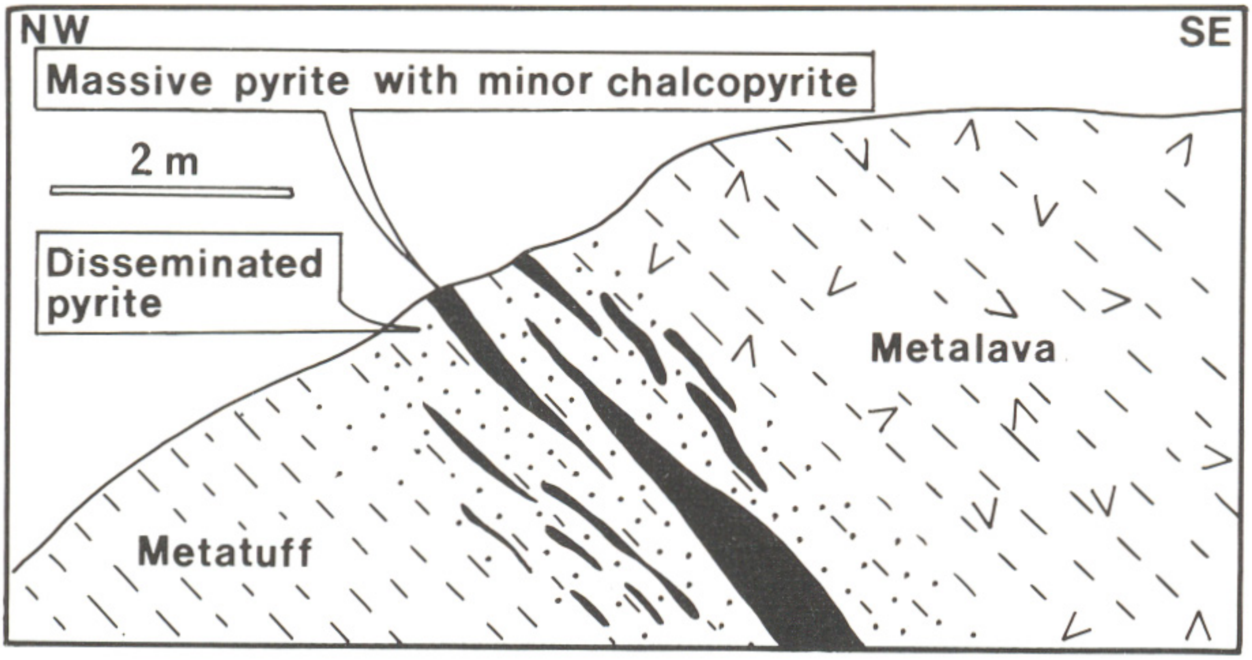

Figure 4. Schematic cross-section illustrating the strata-bound mineralisation at the Xilayani prospect, No. 27 (Bitzios et al., 1981).

4.3. Tertiary Volcano-Sedimentary Basins

Several important polymetallic mineral prospects occur within the Tertiary volcano-sedimentary basins of the central and eastern Rhodope. Three main types of mineralisation exist: (1) fault controlled, (2) strata-bound and (3) porphyry style. The St. Philip prospect (No. 29) represents the most significant area of base metal mineralisation in the eastern Rhodope region. It has known reserves of 1.2 million tonnes of ore at a grade of 9% combined Pb+Zn, with 50-150 ppm Ag. Sulphide mineralisation occurs as a fracture filling within a major NNW-SSE trending fault system (Fig. 5). According to Sanderson et al. (1986), this fault system is a left-lateral strike-slip fault which develops subsidiary (mineralised) 125° trending extensional fractures. This observation is an important one because the much larger Bulgarian deposits to the north are also developed along NNW trending fractures with many of the major lodes occurring in associated 125° fracture systems.

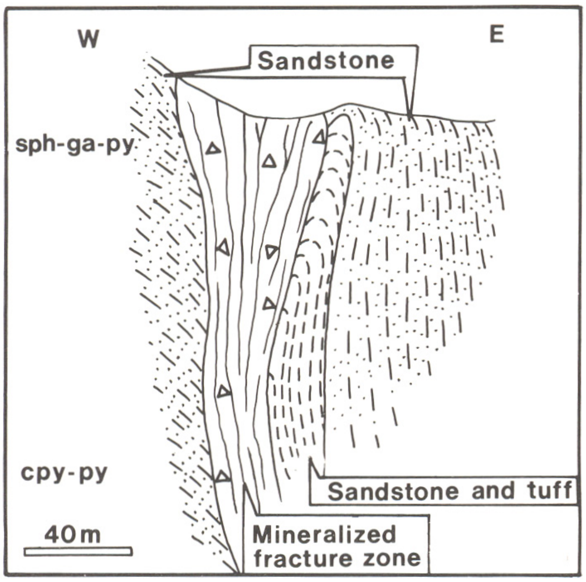

Figure 5. East-west cross-section of the St. Philip mine, prospect No. 29, in eastern Rhodope (Ashworth et al.,1988, Fig. 3, p.175).

The King Arthur prospect (No. 30) lies 4 km north of the St. Philip mine. Mineralisation occurs in small veinlets and impregnations in brecciated zones along a NNW-SSE fracture system and comprises galena, sphalerite, chalcopyrite and pyrite (Govett and Galanos, 1974). The King Arthur fault zone, which may lie on an extension of the St. Philip fracture system, separates Tertiary silicic volcanics from basement metamorphic rocks. This important observation suggests that mineralised fracture systems that cut the metamorphic basement are Tertiary in age (see Sect. 5).

Fracture controlled mineralisation also occurs in the Pefka area (prospect No. 37). Although base metals are related to silicified fracture zones, there is a close spatial relationship between mineralisation and Tertiary volcanic and sub-volcanic rocks.

Another important style of mineralisation associated with Tertiary rocks is the stratiform mineralisation of the Kirki-Essimi-Virini basin. This type of mineralisation is found in sub-economic levels in the Mili area of Essimi (No. 34). At Mili, pyrite, sphalerite, chalcopyrite and galena occur in discontinuous bands within a 30-m-thick sequence of calcareous siltstone and fine-grained sandstone. The stratiform mineralisation at Mili appears to be spatially related to an extensive, possibly deep-seated north-south fracture system and to felsic intrusive, which occur beneath the mineralised area (Ashworth et al., 1986; Arvanitides and Katirtzoglou, 1985).

In addition to the stratiform mineralisation at Mili, small occurrences of porphyry-style pyrite-chalcopyrite mineralisation occur. These are associated with the alteration zones of high level intrusive, which are present in the area (Kalogeropoulos and Katirtzoglou, 1986) and their economic potential appears to be limited.

5. Discussion and Concluding Remarks on Mineral Potential

The preceding sections have attempted to give a brief overview of the varying styles of mineralisation in the whole of the Rhodope area. From the exploration viewpoint, we need to identify those types of mineralisation that have the most promise and arrive at an exploration strategy which will find extensions of known deposits and provide guidelines for a future search programme. Overall, it is clear that the style of mineralisation changes rather dramatically from west to east across the Rhodope. This is clearly a reflection of the changing rock types, as the major marble horizons of the west give way to amphibolite-gneiss complexes and younger sedimentary basins of the east. However, despite this variation, the predominant style of mineralisation is base metal sulphides in vein systems. In our view, this broad pattern of mineralisation throughout the Rhodope suggests that irrespective of the age of the host rock, the vein systems are largely contemporaneous. It follows from the occurrence of mineralisation in the volcano-sedimentary basins that all of the vein-type mineralisation is lower Tertiary in age. In the following sections we examine the evidence for this view.

5.1. Age of Mineralisation

There are two principal lines of evidence supporting the Tertiary age of the mineralisation. These are structure, and lead isotopes. It is evident from the work of Sanderson et al. (1986) that the development of the volcano-sedimentary basins was in response to a major extensional tectonic event and that the same stress regime can be used as the basis for the development of the major fracture systems. Remote sensing and ground truth observations confirm that the fracture systems within the Tertiary basins are also found in the basement rocks. Hence, these data suggest that the development of the basins, and the subsequent mineralisation of the associated fracture system, are all part of the same tectonic package. In support of this model, we point to the similarity in structural control between the major Tertiary deposit of St. Philip (deposit 29) and the smaller fracture-controlled mineralisation within the basement rocks at Aberdeen (deposit 31). At the St. Philip mine, Sanderson et al. (1986) have shown that the fractures are produced by dilation or pull-apart at the termination of NNW left-lateral wrench faults. This results in a set of ESE extensional fractures that are commonly mineralised as are the NNW fractures. At Aberdeen, the mineralisation occurs within basement amphibolites and is found at the intersection of NNW and ESE fractures. We take this to indicate that the mineralisation is Tertiary.

The second line of evidence concerning the age of mineralisation comes from lead isotope data. Deniel et al. (1986) present data from all of the major mineralisation localities of the eastern Rhodope including the basement veins (Aberdeen), basement stratiform (Baiko), Tertiary vein (Kirki, etc.) and Tertiary stratiform style (Mili). They show that the Pb isotopes are largely homogeneous with high 208/204 ratios (indicating a continental rather than a mantle source), and that on the basis of Pb isotopes it is not possible to distinguish between mineralisation occurring in the basement and that which is found in the Tertiary basins. It is important to point out that these data do not exclude the possibility of older mineralisation, but the isotopes require that if this was the case then the Pb was remobilised and thoroughly mixed during the Tertiary to provide a large uniform reservoir.

5.2. Source of the Metals

It has been suggested in the preceding section that the dominant mineralisation styles are related to a sequence of Tertiary fracture systems, which are themselves related to basin development. Within the Tertiary basins themselves, the dominant mineralisation is Pb and Zn with chalcopyrite being a minor component in all but the 'porphyry' style deposits. Ashworth et al. (1985) and Kalogeropoulos and Katirtzoglou (1986) have both proposed variants of a hydrothermal brine circulation model for this type of mineralisation. In these models, the altered nature of the sub-volcanic intrusives is taken to indicate that they were involved in the hydrothermal circulation and probably provided the heat source.

In contrast to the deposits hosted by Tertiary rocks, the vein and stratiform (Baiko) deposits within the basement Amphibolite-Serpentinite Unit are dominated by Cu. This suggests that the mafic nature of the host rock exerted an important influence on the bulk chemistry of the sulphide mineralisation. Billett and Nesbitt (1986) have suggested that the Cu-dominated mineralisation at Aberdeen is either the result of remobilisation of Cyprus-type Cu deposits originally present in the gabbros (= amphibolites) or more simply represents the operation of hydrothermal solutions scavenging Cu from the mafic rocks. These same authors point to the fact that the mineralisation within the Amphibolite-Serpentinite Unit is commonly found at the faulted contact of the two rock types. This suggests that the fault acted as a suitable pathway for either fluids derived from the serpentinite or for the more ubiquitous hydrothermal circulation system that was driven by the Tertiary magmatism. The homogeneous nature of the Pb isotopes support the latter model. Hence, we suggest that although the source of the Cu was local, the bulk of the evidence suggests that the fluids were circulating through a much large volume of rock.

5.3. Future Exploration

As a general exploration. model we envisage a tectonic situation within the Hellenic Rhodope region in which a destructive plate margin existed in the N. Aegean during the early Tertiary (Papazachos and Papadopoulos, 1977). Magmas resulting from this environment rose into extensional regions of the overlying crust and provided a heat source for circulating hydrothermal systems. The fluids not only scavenged metals from the igneous rocks themselves, but also collected metals from the variety of rocks through which they passed. An important aspect of the model is the genetic linkage between magma genesis, basin development and the fracture system that provided pathways for the solutions. In the western Rhodope, the intersection of fractures with marble horizons allowed the hydrothermal solutions to react with the carbonates resulting in metal precipitation. In the eastern region, the solutions precipitated metals either as fracture fillings (e.g., at Kirki or Aberdeen) or dumped the metals into active sedimentation zones resulting in the Pb-Zn stratiform mineralisation (e.g., at Mili).

Irrespective of the model, it is clear that throughout the Rhodope region the bulk of the mineralisation is, in general, fracture controlled. In our view the immediate spin-off from the present EC-supported programme will be the application and extension of the fracture-pattern study of the type conducted by Sanderson et al. (1986). This work, not only offers immediate target areas that should be investigated, but also provides a kinematic model, which can be tested by future ground and remote sensing observations.

Finally, it should be pointed out that although we have concentrated on one particularly important deposit type, we believe there is much room for work into other types. In particular, preliminary work carried out during this programme suggests that the potential for gold mineralisation is considerable.

Acknowledgements

Financial support for the project was supplied under EEC Contracts No. MSM 133 GR and MSM 124 UK and I.G.M.E. The authors would like to thank both the EEC and I.G.M.E. for permission to publish this work. The interest shown by Dr L. Van Wambeke, Commission of the European Communities and Dr. C. Papavassiliou, I.G.M.E. General Director, are much appreciated.

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