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A review of the morphological varieties of ore bodies in the Madan Pb-Zn deposits, Central Rhodopes, Bulgaria

Rossitsa D. Vassileva, Radostina Atanassova, Ivan K. Bonev

Abstract. The Madan Pb-Zn deposits are characterized by three morphogenetic types of ore bodies: veins, stockworks and replacement skarn-ore bodies. The subvertical veins and complex stockwork zones follow the tectonic boundaries of the NNW striking structures, cutting the various gneisses, amphibolites and marbles of the host metamorphic complex. Veins represent regularly-shaped, simple, steeply-dipping mineralized sections of the ore-bearing faults. Apophyses are common, generally joining the main vein in depth. Irregular in shape complex stockwork bodies are represented by sulphide veinlets and impregnations in deeper levels of the deposits and formed in zones with intensive hydrothermal alteration. Complex replacement metasomatic ore bodies are developed at the intersections of the ore-controlling faults with the marbles. Their morphological varieties include bed-like, columnar, mushroom-like or irregular, single or multilayered skarn-ore ledges, controlled by the lithological contacts of the skarns and marbles and screened by the other silicate rocks. The morphology of the replacement bodies is additionally complicated by post-depositional tectonic movements.

The investigation summarizes the available data about the morphology of the ore bodies in the Madan district, taking into consideration the controlling factors. Understanding of the processes in the hydrothermal system and factors determining the deposition of rich ores can serve for the future successful exploitation of the deposits.

Key words: hydrothermal veins, complex stockwork zones, replacement ore bodies, skarns, Pb-Zn deposits, sulphide mineralization, Madan district, Central Rhodopes

Address: Geological Institute, Bulgarian Academy of Sciences, 1113 Sofia, Bulgaria;
E-mail: rosivas@geology.bas.bg

Росица Д. Василева, Радостина Атанасова, Иван К. Бонев. Обзор на морфологичното разнообразие на рудните тела в Маданските Pb-Zn находища, Централни Родопи

Абстракт. Маданските оловно-цинкови находища се характеризират с три морфогенетични типове рудни тела: жили, прожилково-щокверкови зони и метасоматични скарново-рудни тела. Субвертикалните жили и сложни щокверки следват тектонските контакти на ССЗ структури, сечащи гнайси, амфиболити и мрамори на вместващия метаморфен комплекс. Жилите представляват прости, стръмнозападащи минерализирани участъци от рудовместващите разломи. Често се срещат апофизи, които се сливат с основната жила в дълбочина. Прожилково-щокверковите зони с неправилна форма, характерни за дълбоките нива на находищата, са представени от сулфидни жилки и впръслеци в интензивно хидротермално-обработени скали. Сложните метасоматични рудни тела се развиват при пресичането на рудоконтролиращите разломи с мраморни нива. Тяхното мофоложко разнообразие

включва пластообразни, тръбообразни, гъбообразни или неправилни по форма, единични или многослойни скарново-рудни залежи, контролирани от литоложките контакти на скарните и мраморите. Морфологията на тези тела е допълнително усложнена от следрудни тектонски движения.

Настоящото изследване обобщава наличната информация за морфологията на рудните тела в Маданския район, отчитайки основните контролиращи фактори. Разбирането на процесите в хидротермалната система и факторите определящи отлагането на богати руди може да служи за по-нататъшно успешно разработване на находищата.

Introduction

Base-metal hydrothermal deposits in the Madan area, Central Rhodopes are known and exploited for Pb and Zn since ancient (Thracian) times, and later by Saxon miners in the Middle ages. During the second half of 20th century the extensive underground mining in more than 50 deposits of the area led to a production of more than 100 million tons of ores with mean content of 2.5% Pb and 2.1% Zn (Milev et al. 1996). Due to the economic situation after 1990 most of the deposits were ranked unprofitable and many of the underground mines were closed. Presently, the Kroushev Dol, Petrovitsa, Gyudyurska, Erma Reka and Murzian mines still keep operating in the area, together with those of Djurkovo and Govedarnika in the Laki ore district. Considerable ore reserves are still available and the mines have a potential for development.

The Madan district comprises the largest and richest Pb-Zn ore accumulation in the Rhodopes. Together with Thermes in Greece, the Rhodopean districts produced total amount of about 6 million tons metals, which defines the region as a giant Pb-Zn ore concentration.

The replacement Pb-Zn ore bodies in Madan are preferably hosted by early manganoan skarns, which in turn are formed by vein-derived hydrothermal solutions, causing replacement of marble interbeds within high-grade metamorphites. The occurance of manganoan skarns worldwide is generally connected with such base-metal ore mineralizations (Zhao & Li 2003; Meinert et al. 2005).

Understanding of the processes of ore deposition requires detailed study of the ore bodies, host rocks, ore textures and mineral relationships on all scales. The intensive underground mining exploration and exploitation in the Madan deposits allow in-situ observations on the mineral composition, morphology, extent, position and relationships of the ore bodies and their contacts with the embedding rocks. The knowledge of the morphological characteristics of the ore bodies could improve the effectiveness of exploitation process (Megaw 1998).

The purpose of this work is to summarize and analyze the data available on the morphology and variability of ore bodies in the Madan region, collected through systematic field observations and underground documentation.

Previous studies

First summarized data about the Pb-Zn deposits in Central Rhodopes is given by Bonchev (1925). Since than, and especially after the 1960, numerous authors have been working on the mineralogy, geochemistry, genesis and evolution of the hydrothermal mineralization of the Madan deposits (e.g. Kostov 1948; 1963; Kirov & Mincheva-Stefanova 1962; Terziev 1963; Mincheva-Stefanova & Gorova 1965; Eskenazi et al. 1977, 1979; Chiflidjanov, 1979; Piperov et al. 1977; Bonev & Piperov 1977). Numerous studies exist also on the source of metals and age of mineralization (Arnaudov et al. 1990; Amov et al. 1993; Kaiser-Rohrmeier et al. 2005; Marchev & Moritz 2006) and others. Description of the general geological setting, types and morphology of the ore bodies is given by Bogdanov (1960, 1961); Dokov et al. (1962); Bonev (1982, 1995, 2002); Kolkovski & Manev (1988); Kolkovski et al. (1996); Marchev et al. (2005); Vassileva (2002); Vassileva et al. (2005).

Data on some of the world's largest Pb-Zn deposits with replacement bodies similar to those in the Madan ore district are summarized by Einaudi et al. (1981): Santa Eulalia, Chihuahua, Mexico producing over 32.0 Mt ores with 10% Zn and 13% Pb (Megaw et al. 1988); Tetyukhe in Dalnegorsk, Russia; Trepcha in Kossovo (13.7 Mt, 3.8% Zn, 8.6% Pb); Olympias, Madem Lakkos, Mavres Petres at Chalkidiki Peninsula; Sasa in Macedonia; Campiglia Marittima in Toscana, Italy (Capitani & Mellini 2000), Dapai and Baijiazi deposits, China (Zhao & Li 2003), Ban Ban, Australia (Ashley, 1980); Groundhog mine, New Mexico, USA (Meinert, 1987).

Geological background

The hydrothermal Pb-Zn deposits in the Central Rhodopes are hosted in the Rhodopean metamorphic complex, consisting of various gneisses, amphibolites, mica schists, and certain marble layers, intruded by rare pre-ore rhyolitic dykes. The metamorphic massif outcrops in southern Bulgaria and northern Greece and is considered as the inner-most zone of the Alpine-Himalayan orogenic system in the Eastern Mediterranean. Ivanov (1989) and Burg et al. (1990, 1996) interpret the Rhodopean massif as complicated Alpine nappe structure with metamorphic basement of magmatic and sedimentary protoliths, metamorphosed in amphibolite facies, which undergone subsequently compressional and extensional phases. The central parts of the Rhodopean massif are regarded as a large core complex, named Central Rhodopean (Madan) Dome (Ivanov 1989; Ivanov et al. 2000). The core of the Dome, named Arda unit (Ivanov et al. 2000) is constituted by high-grade ortho- and parametamorphites, affected by intensive magmatization and anatexis (Cherneva & Georgieva 2005). The overlying in the south-western part, allochtonous Madan unit is dominated by less migmatized gneisses (Raeva & Cherneva 2009, this volume). The boundary between these two tectonic units is marked by the Madan detachment fault-zone (Dragiev 1988; Ivanov et al. 2000).

Large vein and replacement meso- to epithermal Pb-Zn deposits in the Central Rhodopes are formed in several separate ore districts - Madan, Laki, Ardino, Davidkovo (Fig. 1). Madan district is developed on the south-western slopes of the Dome. Ore deposits occur also in its northern (Laki ore field), eastern (Ardino ore field and Enyovche deposit) and southern (Thermes) incline. Davidkovo is situated on the culmination of the dome-like structure.

The ore bodies in the Madan deposits consist of ore veins, complex stockwork zones and replacement skarn-ore ledges. The veins and stockworks are controlled by six large NNW striking faults in the western slope of the Dome (Dokov & Popov 1963; Kolkovski et al. 1996), whereas gently dipping bed-like and irregular manganoan skarn-ore bodies (Dokov et al. 1962; Vassileva & Bonev 2003) are formed at the intersections of the faults with the three major marble horizons (labelled I, II, and III) of the Rhodopean metamorphic complex. The deposits in the Laki district represent a combination of closely related veins and replacement bodies, while in Davidkovo vein type bodies prevail (Kolkovski & Dobrev 2000). In the area of Ardino, the ore bodies are predominantly of replacement type (Bonev 1991; Bonev & Yanev 1992). In the eastern slope of the Dome ore-bearing faults observed in the Ardino and Enyovche areas strike E-W. The non-mineralized ore-controlling faults in the Madan area have WNW direction (Dokov & Popov 1963; Manev 1975), while in the Ardino district they strike NNW (Bonev 1991). The richest vein and replacement mineralizations of economic importance in the Madan area occur at the intersections of the NNW and WNW fault systems (Kolkovski & Manev 1988), as seen in the main deposits Gradishte, Strashimir, Petovitsa, Mogilata, Ossikovo, Kroushev Dol, Borieva, Giudjurska, Konski Dol, Sharenka, Shumachevski Dol, Karaaliev Dol, Erma Reka.

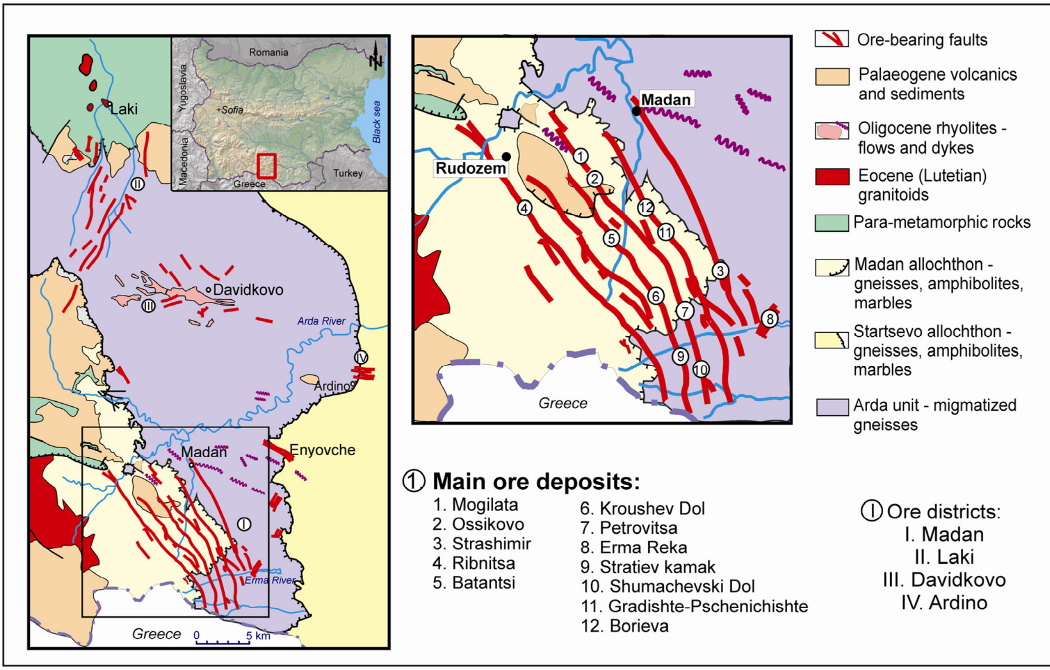

Fig. 1. Simplified geological map of the Central Rhodopean Dome and main ore districts attached to it in Bulgaria (modified after Ivanov 2000)

the Madan deposits, based on Ar^{40}/Ar^{39} measurements on sericite, associated with the main ore paragenesis, reveal mica crystallization ages of 30.76-29.95 Ma (Kaiser-Rohrmeier et al. 2005). The obtained data for Laki (~ 29.3 Ma) show age differences of about 1 Ma. Alteration related muscovite from the Enyovche deposit gives slightly older age (31.2 Ma).

Hydrothermal mineralization of the ore-forming system

Mineralization stages

Three main mineralization stages have been established based on mineral relationships (Bogdanov, 1960; Kirov & Mincheva-Stefanova 1962; Mincheva-Stefanova & Gorova 1965; Bonev 1982; Vassileva & Bonev 2001; 2003; Bonev & Vassileva 2004) and microthermometric studies of fluid inclusions in transparent minerals (Krasteva 1977; Kolkovski et al. 1978; Strashimirov et al. 1985; Vassileva et al. 2009).

1. Skarn stage. The earliest stage of hydrothermal mineralization in the area is the skarn formation at the expense of marble horizons in the Rhodopean metamorphic complex. The geochemical specialization of the skarns, widely distributed in the Madan area is manganoan. They are composed of pyroxenes from the hedenbergite-johannsenite solid solution series and later overprinted by manganoan pyroxenoids. Several characteristics distinguish these skarns as a separate geochemical and petrological formation. The exoskarns are of infiltration type, distal, without visible links to magmatism and no direct link to any intrusion. Temporally, these skarns are clearly pre-ore, without any primary sulphide formation. Their retrograde hydrothermal alteration, however, results in the formation of a favourable medium for sulphide deposition (Vassileva & Bonev 2003). The skarns exhibit well expressed zoning defined by changing Mn/Fe ratios across lateral and vertical direction (Vassileva 2004). Compared to other skarn types (Meinert et al. 2005), manganoan skarns are formed at relatively lower temperatures. Microthermometry of fluid inclusions in some pyroxenes revealed *Th* 420-400°C (Vassileva et al. 2009).

2. Main ore stage. Several main ore parageneses are deposited during this stage: quartz-pyrite, quartz-galena, quartz-sphalerite-galena (Kolkovski & Dobrev 2000; Bonev & Vassileva 2004 and references therein). Main ore minerals are galena, sphalerite, pyrite and chalcopyrite. Galena prevails over sphalerite in the veins, while sphalerite is more abundant in the skarn-ore replacement bodies. Subordinate ore minerals are arsenopyrite, tennantite-tetrahedrite, pyrrhotite, sulphosalts of Ag and Bi. The temperature of formation of sulphide assemblages, according to the fluid inclusion data, is relatively high: 350-300-280°C (Strashimirov et al. 1985; Kolkovski et al. 1978, 1996; Kostova et al. 2004; Kotseva et al. 2008; Vassileva et al. 2009). The major sulphide deposition is utilized by the immediately preceding retrograde alteration of the manganoan clinopyroxenes. The acid wall-rock alteration in the silicate rocks is of quartz-sericite type.

3. Late post-ore stage. The stage includes the deposition of late gangue mineralization represented by carbonates, quartz and chalcedony, barite, as well as few scarce sulphides and sulphosalts. The temperature of formation of this assemblage, obtained by microthermometric studies of fluid inclusions in transparent minerals is in the range 260-200-180°C (Strashimirov et al. 1985; Vassileva & Bonev 2001; Vassileva et al. 2009). In a study of fluid inclusions in sphalerite from several Madan deposits, Bonev & Kouzmanov (2002) reported *Th* 220-200°C for the primary fluid inclusions and *Th* of 185-160°C for the secondary ones.

The stage is contemporaneous with intensive post-ore tectonic movements, complicating the morphology of the ore bodies.

Physical chemistry of the hydrothermal fluids

The composition of the ore-precipitating fluids is a key aspect in the interpretation of ore deposition in the hydrothermal system. The obtained information is from fluid inclusion studies in galena (Piperov et al. 1977) and quartz (Kostova et al. 2004; Kotseva et al. 2008).

Fluid chemistry of the liquid phase determined from fluid inclusion studies represents diluted, slightly acid (pH near 6.5) and reducing (Fe^{2+} and Mn^{2+} ~ 0.3 g/l) Cl-Na-K aqueous solutions with salinity of 4-4.5 wt.% $NaCl_{eq}$ (Piperov et al. 1977). Direct chemical analyses reveal no measurable S-containing components in the fluid and mean Na:K:Ca ratio of 11:2:1. Water vapour and low CO_2-content (0.4 wt.%), with highly variable CO_2/H_2O ratio, are the main constituents of the gas phase. No presence of N_2 and O_2 is determined. Fluid inclusion microthermometric and chemical data (LA-ICP-MS) of the Yuzhna Petrovitsa deposit revealed, that galena and sphalerite precipitated from a slightly acid fluid with a Pb content of 7-8 ppm and a Zn content of about 33 ppm (Kostova et al. 2004). Similar data about the Kroushev Dol deposit (Kotseva et al. 2008) showed mean values of Pb 29, Zn 70, Cu 16, As 34, Bi 5 and Sb 23 ppm and mol ratio ranges: K/Na 0.053-0.22; Ca/Na 0.016-0.065; Mg/Na 0.002-0.009 and Mn/Na 0.001-0.010 in the ore-forming fluids with salinity of 4.0-9.1 wt% $NaCl_{eq}$. The late stage sulphides are precipitated by fluids with relatively low salinity of 5-6 wt.% $NaCl_{eq}$. (Bonev & Kouzmanov 2002).

$\delta^{34}S$ of sulphides varies from 0 to 6-7‰ with a trend to decrease from north to south (Bonev et al. 2000). The composition of stable isotopes in the fluids reveals values for δD in the range from -40 to -80‰ (mean -55‰) and $\delta^{18}O$ from 0 to -10‰ indicating predominantly meteoric origin of waters (Bonev et al. 1997). $^{87}Sr/^{86}Sr$ isotopes of barite (0.71126 to 0.70946) and Pb isotope ratios of galena ($^{206}Pb/^{204}Pb$ 18.68-18.75; $^{207}Pb/^{204}Pb$ 15.66-15.70; $^{208}Pb/^{204}Pb$ 38.86-39.05) according to

Marchev & Moritz (2006) suggest magmatic hydrothermal origin for the base-metal deposits in the Central Rhodopes, with strong contribution from the host metamorphic rocks and mixing with large amount of meteoric waters. The metal transport is accomplished by chloride complexes stable in acid conditions and destructed on their neutralization during fluid/rock interaction.

Morphological types of ore bodies

Main morphogenetic types of ore bodies in the Madan Pb-Zn deposits can be subdivided into the following distinct categories: simple ore veins; complex stockworks and replacement bodies (Table 1). These types often co-exist in one and the same deposit, showing close connections and transitions from one type to another.

Vein ore bodies

Veins comprise regularly-shaped, simple, single, steeply-dipping mineralized bodies, as parts of the ore-bearing NNW fault zones (Dokov & Popov 1961; Kolkovski & Manev 1988). As veins are hosted by certain fracture system they show regularities in their orientation throughout the whole ore district. Their thickness varies between 20-40 cm and several meters, rarely reaching tens of meters. The contacts with the embedding gneisses are sharp (Fig. 2a), sometimes clearly tectonic. Apophyses are common, generally joining the main vein in depth. Upper parts of the veins often split to form horse-tail-like structures (Kolkovski et al. 1996). The vein filling may consist of single mineral (galena or sphalerite), but normally they are composed of quartz-sulphide aggregates. Sometimes, the ores reveal banded structure (Fig. 3). In such cases, the separate bands have different mineral compositions, deposited one after another in open space. Ore textures in the veins are massive, breccias, crustifications, druses. The quantity of galena often prevails over sphalerite. The Pb/Zn ratio varies in the range 1.2-2.0. Large veins are typical for the deposits of Strashimir, Pshenichishte, Spoluka, Kroushev Dol, Shoumachevski Dol, Shadiitsa, Goliam Palas.

Stockworks

Stockwork zones are genetically and spatially connected to the veins. This morphogenetic type is characteristic for the relatively deeper levels of the deposits, where steep ore-bearing faults are marked by strong alteration of the gneisses. The mineralized stockwork zones are

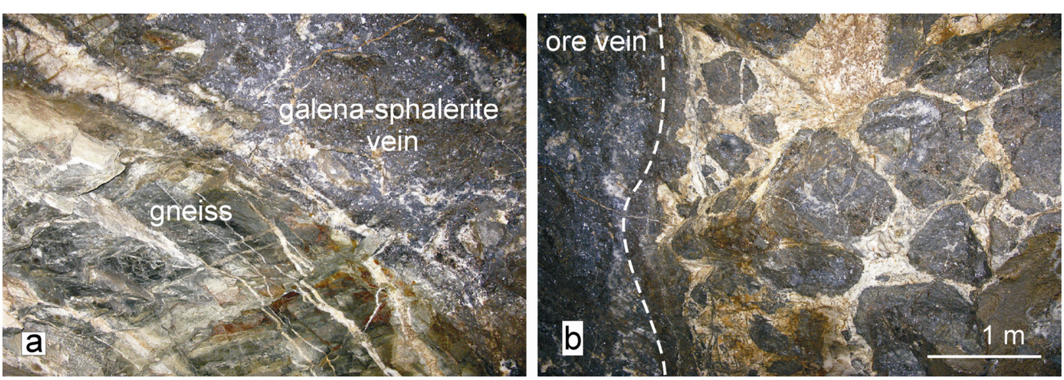

Fig. 2. Sharp contact between the ore vein and hosting gneiss (a) and brecciation around the ore vein (b) in the Kroushev Dol deposit, mining level 450

Table 1. *Morphogenetic types of ore bodies in the Madan Pb-Zn deposits (modified after Bonev 2002)*

General characteristics	Simple ore veins	Complex stockwork zones	Skarn-ore bodies
Morphology	Single mineralized open fractures	Stockwork zones of small veins and veinlets, with brecciation and ore impregnations	Gently slopping bed-like, mushroom-like, columnar or irregular-shaped metasomatic bodies
Size	1-3 m width; up to 1-2 km length	Up to 10-20 m width; 1-2 km length	30-60 m width, 20-25 m thickness
Main ore and gangue minerals	Galena, sphalerite, pyrite, chalcopyrite; Quartz and carbonates	Sphalerite, galena, pyrite, chalcopyrite; Quartz and carbonates	Sphalerite, galena, pyrite; Johannsenite-hedenbergite, rhodonite, carbonates, quartz
Host rocks	Various gneisses and amphibolites	Various gneisses and amphibolites	Marbles
Products of wall-rock alteration	Thin zones of quartz-sericite-chlorite-epidote-carbonates	Wide zones of quartz-sericite-chlorite-epidote-carbonates	After skarns: Mn-amphiboles, bustamite, pyroxmangite, manganilvaite, carbonates, quartz
Ore textures	Massive, crustifications, druses, breccias	Impregnations, disseminations, breccias, massive	Massive, banded, rhythmic-banded, radial, druses, nests, impregnations
Condition of ores	Rich ores (10 and more % metals)	Intermediate quantity ores; several % metals, abundant quartz	- rich massive and banded ores (10 % metals) - impregnations in altered skarns
Pb/Zn ratio	> 1; galena prevails	≤1; sphalerite ≈ galena	≤1, sphalerite prevails
Fluid transport	Convection	Convection + diffusion	Diffusion (+ convection)
Water/rock interaction	Limited in thin areas	Intensive, large areas	Internsive – alteration after skarns
Mechanism of ore deposition – neutralization of the ore transporting acid fluids	Deposition of rich ores by boiling over the critical level; under that level – barren quartz and banded ores (zonal deposition)	Intensive reaction with the host gneisses and deposition of sulphides + quartz; limited boiling in the upper levels	Retrograde alteration of skarns and ore deposition; direct crystallization in voids of "hydrothermal karst" + limited boiling
Perspectives in depth	Over the critical level, in parallel zones	In deeper levels, poor ores	Perspective on all levels
Representative deposits	Strashimir, Spoluka, Pshenichishte, Goliam Palas, Kroushev Dol, Shoumachevski Dol	Ribnitsa, Stratiev Kamuk, Erma, Enyovche	Gradishte, Borieva, Kroushev Dol, Mogilata, Ossikovo, Petrovitsa, Enyovche, deep levels of Erma

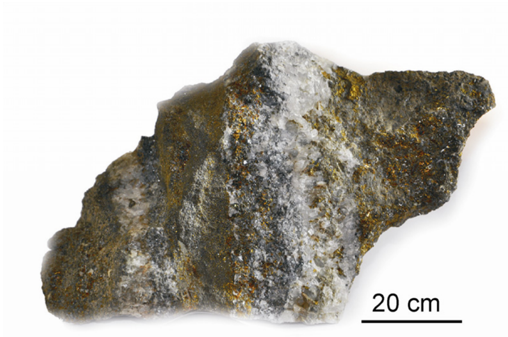

Fig. 3. Banded polymetallic ores

represented by disseminated ores in thin, irregularly-shaped, discordant sulphide veins and veinlets, impregnations and breccias (Table 1). They are 1-2 to 10-20 m wide and up to 1-2 km long. Their mineral composition is dominated by sphalerite, galena, pyrite and chalcopyrite. The quantity of sphalerite is almost equal to that of galena with characteristic Pb/Zn ratio of 0.8-1. The host rocks are strongly hydrothermally altered, showing unclear contacts. Signs of large scale, intensive water/rock interaction are evident around the fault zones. Stockworks are typical for the deposits of Ribnitsa, Stratiev Kamuk, Pechinsko, Enyovche.

Replacement ore bodies

Replacement ore bodies are the most interesting ones from genetic and economic aspect (Bonev 2002) and variable from morphological point of view (Dokov et al. 1962). They are always embedded in the marble horizons of the Rhodopean metamorphic complex and host rich ores of economic importance. Their width is generally 30-60 m, sometimes even more. The thickness depends on that of the hosting marble layer and is mostly 4-5m, rarely reaching up to 20-25 m. Main minerals are presented by johannsenite, hedenbergite, rhodonite, sphalerite, galena, pyrite, carbonates and quartz.

The *zoning in replacement bodies* is primary (metasomatic), determined by the chemical variations typical for the metasomatic replacement fronts creating primary skarn assemblages (Bonev 2003; Bonev & Vassileva 2004; Vassileva 2004) and secondary, overprinted during the ore deposition. The clinopyroxenes from the johannsenite-hedenbergite series are the major constituent of the manganoan skarns embedded in the marbles. Their zoning in lateral direction is expressed by mostly ferroan clinopyroxenes (hedenbergite) in the inner parts, close to the feeder faults, while the manganoan ones (johannsenite) are at the periphery of the bodies. More complex is the secondary zoning, due to retrograde alterations of skarns and sulphide overprinting with variable mineralogical, quantitative and textural relationships. In the process of hydrothermal retrograde alteration clinopyroxenes are altered to a highly-manganoan assemblage of manganoan amphiboles, pyroxenoids, manganilvaite and carbonates (Vassileva & Bonev 2003). Since the manganoan members of the hedenbergite-johannsenite series are considerably more stable in the sulphidation environment, the Fe-containing skarn pyroxenes in the proximal zones, along the veins, are nearly fully replaced by rich sulphide ores, whereas in the distal outermost zones the highly manganoan pyroxenes and rhodonite often remain unchanged. Texturally the secondary zoning is expressed by massive sulphide ores close to the ore vein, followed by a zone of thin- and thick banded ores and spread single nests and impregnations of sulphides at the distal zones and at the periphery of the ledges, where unaltered radiate pyroxene aggregates prevail. A generalized section of metasomatic ore body with typical mineral zoning is presented on Fig. 4.

Ore textures in the replacement ore bodies are radial, rhythmic-banded, impregnations, massive, nests and druses (Bonev 2001). The massive, coarse-grained metasomatic sulphide ores are characterized by high porosity. A system of open space cavities are often developed within the skarn bodies as a result of selective dissolution mainly of the retrograde carbonates. Offering a system of channelways for fluids, the hydrothermal karst is a favourable

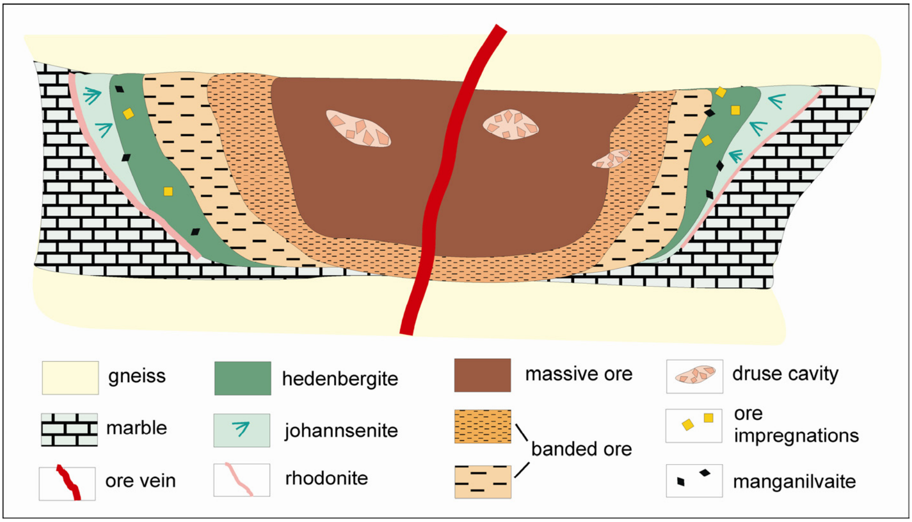

Fig. 4. General distribution of zones in a replacement ore body

space for direct open space druse crystallization of sulphide minerals, carbonates and quartz (Bonev 2003; Bonev & Vassileva 2004).

According to their geological position and morphology, the following subtypes of replacement bodies can be distinguished in the Madan Pb-Zn deposits (Dokov et al. 1962; Bonev 1995; Bonev 2002).

Single beds entirely replacing single, always thin, marble layers with constant thickness of 1-3 m. Such morphological types are known and exploited in the deposits of Pshenichishte (Fig. 5a) and Kralev Dol.

Multilayered beds replacing several relatively thin (1-2 m) marble layers and lenses intercalated by gneiss or pegmatite layers. Such ore bodies are typical for the Nadezhda deposit (Fig. 5b, modified after Dokov et al. 1962). The ore mineralization is unequally developed on both sides of the vein. The metasomatic beds in the hanging wall are wider.

Multilayered sheet-like bodies in the thick (hundreds of meters) Ist marble horizon. This type of ore bodies are represented in the Erma Reka deposit. They are deep seated and therefore detected only by drilling (Chiflidjanov 1979). Owing to the relatively deep position and the huge thickness of the marble layers, the morphology of the metasomatic ore bodies could be extrapolated from the drilling data. Chiflidjanov (1979) states that the ore mineralization is overprinted on the hedenbergite-rhodonite-garnet-epidote skarns, in the upper levels of the Ist marble horizon, just below the screening gneisses.

Massive, *bed-like* skarn-ore ledges, sometimes with irregular morphology, developed around the ore vein in the IInd marble layer. Typical examples are available in the Kroushev Dol deposit (Fig. 5d, e). The deposit has well expressed vertical zoning along the main subvertical ore-bearing fault. In the upper levels (1100-650 m) rich galena-sphalerite ores are formed in the gneiss-embedded vein, under boiling conditions. In depth (600 m) follows a zone of barren quartz (Bonev 2002). The replacement ores are developed in the marble horizons at 450-400 m.

Complex multilayered ledges, replacing several thick marble layers along several large ore veins. Representative deposit is Gradishte.

The replacement bodies are developed both in the IInd and IIIrd marlble horizons (Fig. 6a,b), reaching its maximum thickness in the

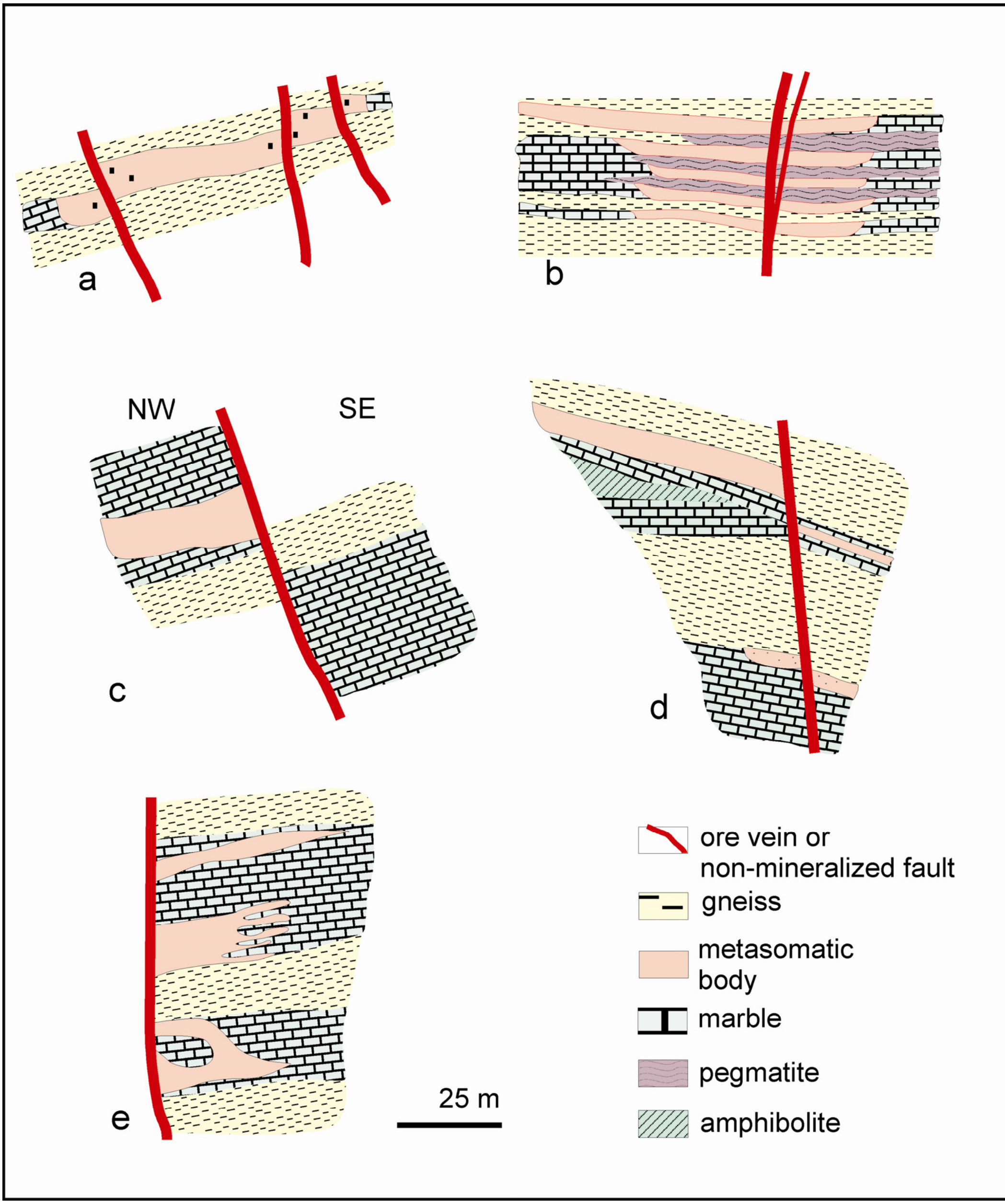

Fig. 5. Sections from several deposits in the Madan region: a) thin marble layers entirely mineralized, Pshenichishte deposit; b) skarn-ore ledges intercalated with pegmatites and gneisses, Nadejda; c) massive bed-like body in the footwall of a strongly denivelated marble layer, Enyovche; d) bed-like bodies around the ore vein, Kroushev Dol; e) irregularly-shaped metasomatic bodies at mining level 450 in the Kroushev Dol deposit

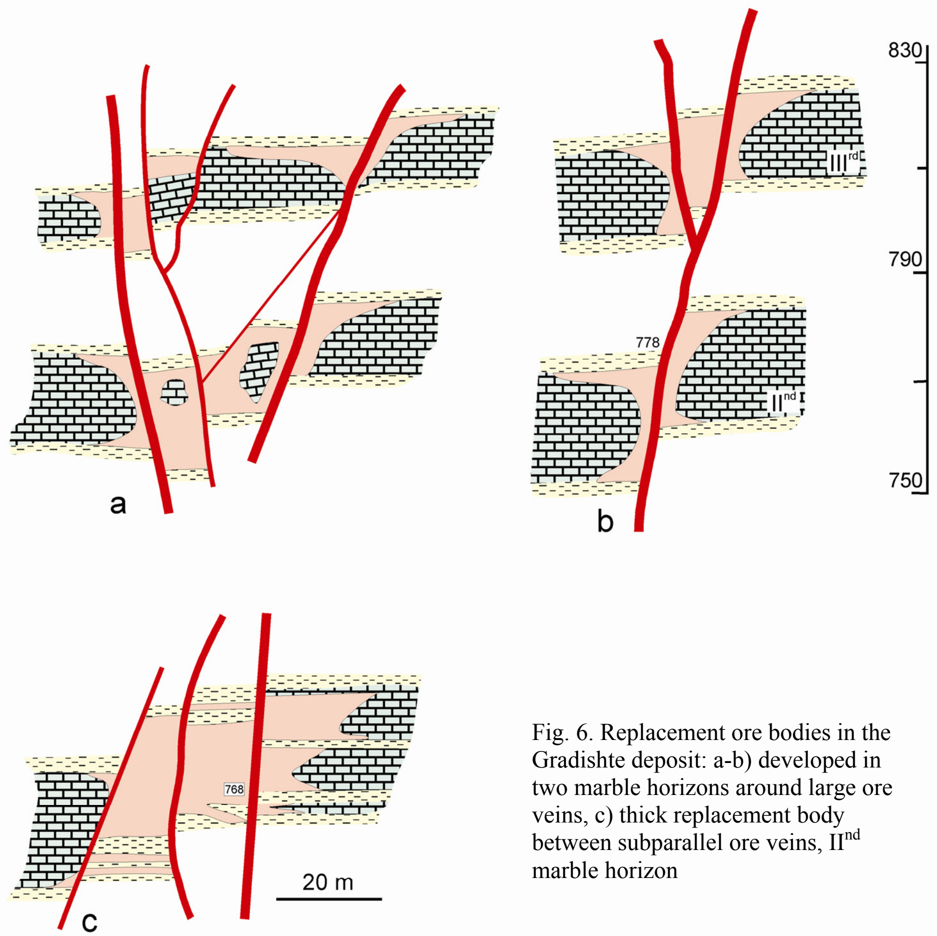

Fig. 6. Replacement ore bodies in the Gradishte deposit: a-b) developed in two marble horizons around large ore veins, c) thick replacement body between subparallel ore veins, IInd marble horizon

zones between two veins (Fig. 6c). These metasomatic ore bodies are wider in the upper parts, below the gneissic screens. Sometimes the lower parts of the metasomatic body also show such wider zones, observed along the boundary of the original marble layer (Fig. 6b). Similar morphology of multilayered beds and lens-like bodies are typical also for the deposit of Petrovitsa.

Vein-like, columnar or mushroom-like and irregular in cross section ore bodies within thick (e.g. 15-20 m) marble horizons along a thin steep non-mineralized fault: Ossikovo (Fig. 7a), Mogilata (Fig. 7b, c, d), Borieva and Gradishte.

Bed-like replacement bodies in the IIIrd marble horizon, developed around the intersection of NNW and WNW fault systems, Sharenka deposit (Fig. 8a, b). The thickness of the skarn-ore ledges reaches 15 m in the central and southwest parts, and inclines laterally to the southeast (Dokov et al. 1962). The primary shape is complicated by later tectonic movements.

Irregular metasomatic bodies with complex shape in cross section embedded in the IIIrd graphite-bearing marble horizon, the Borieva deposit. The replacement ores are associating with and screened by pegmatites (Fig. 8c).

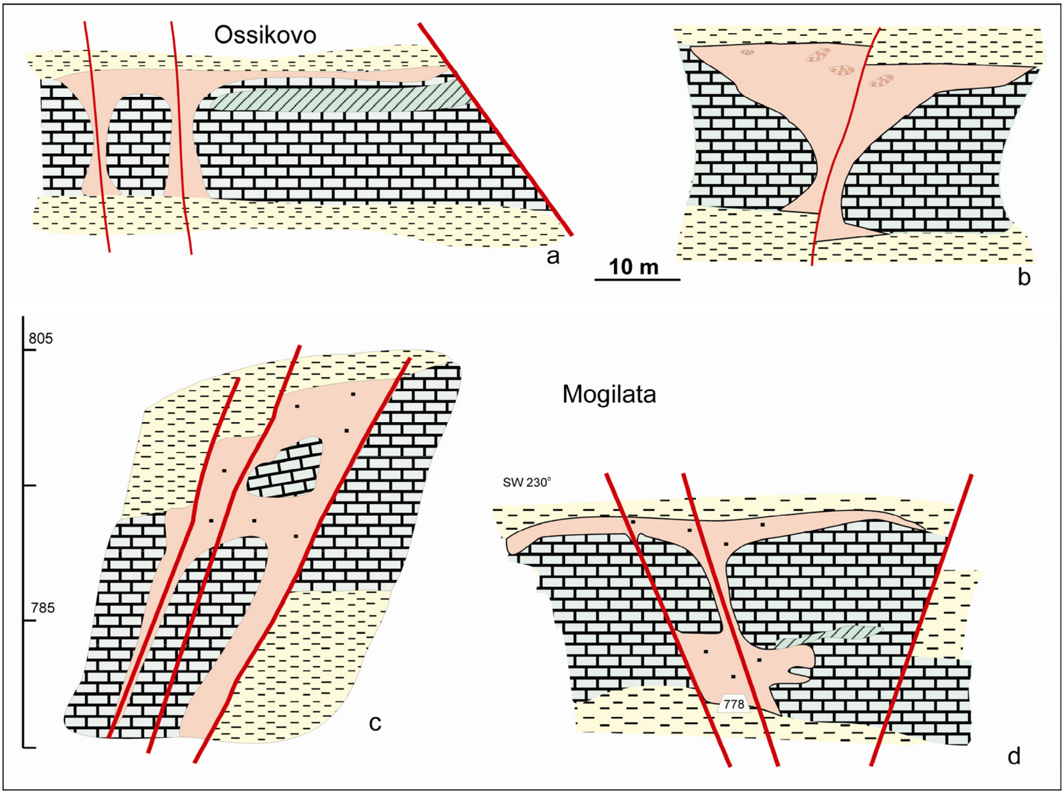

Fig. 7. Columnar, mushroom-like and irregular in shape replacement bodies in the Ossikovo (a) and Mogilata (b-d) deposits, developed around non-mineralized faults

In addition to the cases from Madan district, Bonev (1991) described single thin beds (up to 1-1.5 m) replacing only the lowest marble layer in a thick marble packet along very scarcely mineralized faults; typical for the deposits in Ardino district.

The metasomatic ores are always embedded in the retrogradely altered manganoan skarns. As seen above, their swing of development is highly asymmetric, according to the feeder faults. The complex morphology of these ore bodies results from the variable thickness of the host marbles, the presence of pegmatite or gneiss screens and later post-ore tectonics.

The described types of ore bodies, including their varieties can co-exist in one and the same deposit (e.g. Kroushev Dol, Enyovche deposits). A representative case is the well studied (Minčheva-Stefanova & Gorova 1965; Bonev 1982) and documented deposit of Gradishte (Fig. 6), where large veins co-exist with rich replacement ore bodies.

Factors determining the morphology and size of the ore bodies

Main factors controlling the morphology of ore bodies are the structural and lithological characteristics of the region.

Structural control

The evolution of the hydrothermal system in the Madan Pb-Zn deposits depends on the features of the ore-controlling and non-mineralized faults in the Rhodopean metamorphic complex:

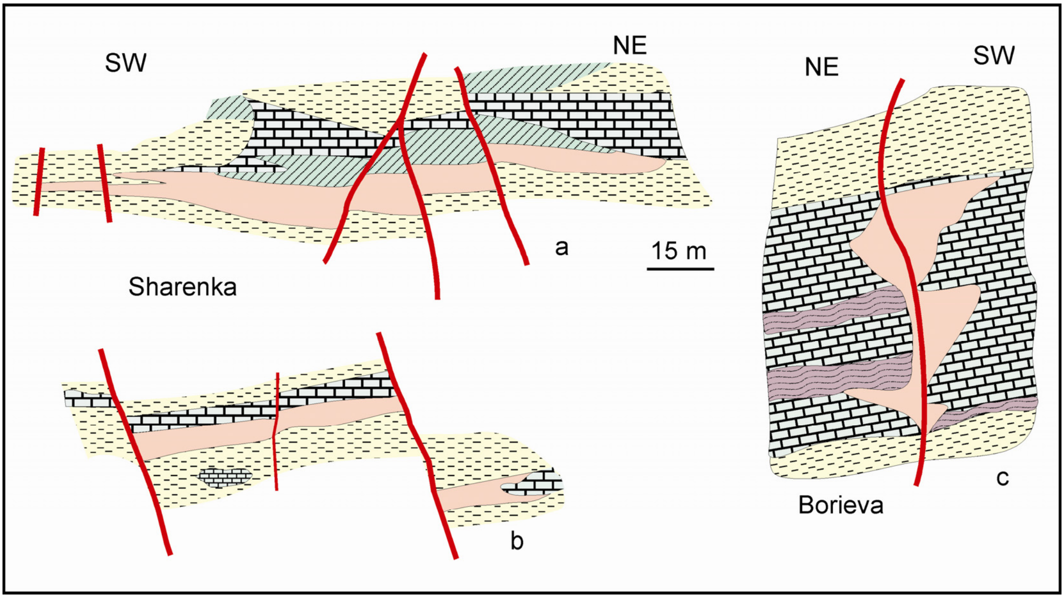

Fig. 8. Cross sections of metasomatic bodies in the IIIrd marble horizon from Sharenka (a, b) and Borieva (c) deposits (modified after Dokov et al. 1962)

- The six steeply-dipping NNW-striking faults in the area are the main ore-conducting and ore-bearing structure (Dokov & Popov 1963). The deposits are genetically connected to this fault system.

- It was pointed out by Kolkovski & Manev (1988) that the economically important mineralizations occur at the intersections with another fault system. The WNW-striking faults represent hydrothermally altered zones, filled with tectonic clay (mostly illite), acting as impermeable screen for the ore-fluids. These faults were not involved in the hydrothermal transport of ore material. Locally they host pre-ore rhyolite dykes, later crosscut by the ore veins. Such relationships are documented in the deposit of Mogilata (Dragiev 1988).

- The so called "Madan detachment fault" (Ivanov et al. 2000) is the earliest of all tectonic structures in the region (determined by geological relationships). The nature of the fault was inappropriately interpreted by Dragiev (1988) and Dragiev & Danchev (1990) as an impermeable shield for the upcoming ore fluids. As a matter of fact it is cut by all the other, later fault systems and ore-deposition takes place both above and below its plane. During the ore deposition the detachment fault was already consolidated and it did not conduct ore fluids (Bonev 2002). The presence of the Madan detachment fault leads to a decrease in the hydrostatic pressure, utilizing the crystallization in open space. For example, the unique, well-known druses of polyhedral sulphide crystals with remarkable size from the Ossikovo and Mogilata deposits are formed at mining levels around 700, near the detachment surface.

- Since the NNW-striking fault system provides pathways for the movement of the ascending hydrothermal fluids, the number, size and position of these faults in certain location controls the scale of the resulting ore deposition (Bonev 1995). Dense systems of adjacent, large faults control the deposition of big and rich vein and replacement ore bodies, like those observed in the Gradishte deposit (Fig. 6). The largest replacement bodies in the ore field are related to large veins, and sometimes to several closely-adjacent veins. In contrast, small, non- or slightly mineralized fault zones produce small replacement ore bodies, only in the upper parts of the marble layers or beneath impermeable screens. Such cases are observed in Mogilata and Ossikovo deposits (Fig. 7).

- The tectonic fragmentariness and permeability of the ore-hosting rocks increase the reactive surface, interacting with the upcoming fluids. The latter is one of the important conditions for the high degree of water-rock interaction as mentioned by Reed (1997).

- Sudden tectonic events (like seismic hits), could provoke adiabatic expansion in the system, causing local supersaturation and precipitation of ores.

- Movements along the ore-bearing and non-mineralized fault structures complicate the morphology of the vein and replacement ore bodies. Such cases can be observed literally in all deposits. An example of complex morphology, due to late fault movements is the mining level 768 in the Gradishte deposit.

Lithology

The three marble horizons in the Madan region (lower – Ist, middle - IInd and upper - IIIrd) are a favorable medium for development of metasomatic processes: formation of manganoan skarns and subsequent deposition of rich sulphide ores therein. The number, thickness, stratigraphic and hypsometric position of the host marble layers determines the morphology of the replacement bodies. The detailed underground works and exploration reveal that the metasomatic ore assemblage is always deposited within the limits of the primary skarn assemblage.

The mineralogical and geochemical data about the thick (~ 750 m) Ist marble horizon is obtained only by drilling in the deposit of Erma Reka. The metasomatic ore mineralization there is genetically connected with skarn bodies. Their mineral composition, typical for the calcic skarns (Gadjeva 1983), differs significantly from those of the skarn ledges in the upper two marble horizons (Vassileva 2002; Vassileva & Bonev 2003).

The second, middle, marble horizon crops out on the left slope of the Gjudjurska River and in the Erma River valley. The ore mineralization there is connected with manganoan skarns. The second marble layer hosts important and representative replacement type deposits in the Madan ore district, such as Gradishte-Pshenichishte, Petrovitsa, Yuzhna Petrovitsa (Dokov et al. 1962), Mogilata, Ossikovo, Kroushev Dol.

The third, upper, marble layer outcrops on present surface in the area of the deposits Buchovitsa, Yuzhna Petrovitsa and Gradishte-Pshenichishte in the southern part of the Madan region, as well as around the Sharenka and Baram deposits in its northern part. A specific characteristic of the IIIrd marble layer is the presence of graphite flakes, oriented parallel to the foliation. These graphite crystals are inherited and preserve their orientation also in the skarn pyroxenes, formed at the expense of the marbles. Such samples are observed in the Kroushev Dol deposit. This marble horizon hosts the replacement bodies of the Gradishte, Borieva, Konski Dol, Sharenka, Petrovitsa and Kroushev Dol deposits.

The morphology of the replacement ore bodies is influenced also by the presence of impermeable gneiss (Gradishte – Fig. 6; Mogilata and Ossikovo deposits – Fig. 7) or pegmatite (Nadejda – Fig. 5b) screens over, or inside the marble horizons. In accordance with the upward direction of fluid movement, the metasomatic replacement is more intensive in the upper parts of the marble horizon, just below the gneisses or the pegmatite screens. Likewise is the pronounced asymmetry of the replacement bodies, systematically better expressed in the hanging walls of the ore-controlling faults (e.g. Fig. 7b, Mogilata deposit). In rare cases replacement ores are observed also in amphibolites (e.g. Murzian deposit).

Mechanisms of ore deposition in the morphogenetic types of ore bodies

The ore deposition in the hydrothermal system of the Madan Pb-Zn deposits is a result of the neutralization of acid fluids, transporting metals as highly-soluble chloride complexes. The neutralization is achieved by specific reaction in the different morphogenetic environments (Bonev et al. 2000):

- Boiling of solutions in the upper parts of the simple ore veins (Strashimir, Kroushev Dol deposits) is an important mechanism for the deposition of rich ores. This process takes place above the critical hypsometric level (Bonev & Piperov 1977; Bonev 2002; Kotseva et al. 2008).
- Intensive fluid/rock interaction causing quartz-sericite alteration of the host gneisses is typical for the stockwork zones. The disseminated ores, deposited by the way of convection and diffusion are relatively poor.
- In the metasomatic ore bodies, the neutralization of acid fluids is performed on reaction with the alkaline infiltration pyroxene skarns. This results in retrograde alteration of the skarns, and deposition of sulphide ores. The Mn-Fe clinopyroxenes are highly reactive in sulphur-containing high-temperature fluids. The formation of manganoan silicates (pyroxenoids, amphiboles, manganilvaite, chamosites, andraditic garnets) and carbonate minerals (Vassileva & Bonev 2003) in the process of lowering temperature and pH of the hydrothermal solutions favors the ore precipitation.

The replacement ores always contain skarn minerals and their relics, as well as skarn alteration products. They are highly porous and cavernous, which is not consistent with the classic ideas for metasomatic formation "volume by volume". The complex history of these ores includes two main crystallization mechanisms: 1. metasomatic growth in solid medium realized by solid-state topotaxic ion-exchange reactions or reconstructive dissolution/precipitation processes; and 2. crystallization in open space.

The remarkable variety of ore textures in the deposits of Madan district is indicative for the mode and local conditions of deposition (Table 1): open space filling (cutting veinlets, druses, crustifications, breccias, etc.) or replacement (impregnations, radiate, rhythmic-banded, and massive). Locally, selective dissolution of some sulphides is also observed (Bonev 2007; Atanassova 2009).

An exploration perspective

The extensive mining works in the region gave the opportunity for direct in-situ observations on the morphology of the ores, their spatial position and relations with the other petrologic varieties in the metamorphic complex. These investigations have direct impact over the exploration and mining activity in the region. As seen from their geological and mineralogical characteristics, zoning and mechanisms of deposition, the three morphogenetic types of ore bodies have different exploitation perspectives (Bonev 2002).

The simple sulphide veins, formed by way of free crystallization in boiling conditions are perspective above the critical level, where rich ores (~10 % metals) are deposited. In depth, these ore bodies do not contain economically important ores.

The stockworks, formed by free crystallization and metasomatism, at deeper levels and in wider zones, but contain ores with low metal content (2-3 %). Their exploitation is complicated further by the intensive hydrothermal alteration and relatively deeper levels of appearance, and they are currently unprofitable.

The metasomatic bodies concentrate an important part of the ore resources of the Madan district. Since they are perspective in all levels of the deposits they can be considered as a potential future resource for base metals in the region.

Conclusions

The general morphogenetic types of ore bodies in the Madan Pb-Zn deposits are simple veins, complex stockwork zones and metasomatic skarn-ore bodies.

The morphological diversity of the ore bodies in the Madan Pb-Zn deposits is controlled by physicochemical, mineralogical, lithological and structural factors. It was shown that structural control is the main controlling factor for the morphology of the ore veins and stockwork zones, while the morphology of the replacement ledges is lithologically controlled by the shape of the earlier skarn replacements and respectively by the hosting marble layers.

High-grade vein ores and replacement bodies of the Madan ore district are the most important future mining resource in the region of the Central Rhodopes. Their prospecting and exploration is facilitated by the available knowledge about the processes of their formation and localization.

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