SE Europe Geoscience Foundation

SE European Conference and Field Trip

7th May – 10th May 2005, Sofia, Bulgaria

Carpathian Gold Inc., Ivanhoe Hereward Bulgaria EAD,
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FIELD TRIP GUIDEBOOK

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Sofia University "St. Kliment Ohridski", University of Mining and Geology "St. Ivan Rilski"

Sofia SEG Student Chapter

Sofia, May 2005

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Program

May 6th

14:00 – 19:00	Arrival, Registration, Serdika Hotel
20:00 – 22:00	Cocktail party, Sofia University "St. Kl. Ohridski"

May 7th

8:00 – 8:30	Opening ceremony, Sofia University "St. Kl. Ohridski" - Aula
8:30 – 9:00	Morning coffee
	Invited Lectures:
9:00 – 9:30	Christiana Ciobanu, /Regional geology and mineralization of SE Europe/
9:30 – 10:00	Lawrence Drew, /Regional structure of SE Europe/
10:00 – 10:30	Jeremy Richards, /Porphyry Copper Deposits/
10:30 – 11:00	Coffee break
11:00 – 11:30	Tim Baker, /Porphyry Gold Deposits/
11:30 – 12:00	Rena Guenduez, /Sustainable development/
12:00 – 13:00	Lunch
13:00 – 15:00	Company presentations
15:00 – 15:30	Coffee break
15:30 – 17:30	Company presentations

May 8th

8:00 – 10:00	Travel to Panygurishte - bus
10:00 – 12:00	Assarel open pit
12:00 – 13:00	Lunch
13:00 – 17:00	Panygurishte porphyry and epithermal copper-gold deposits
18:30 – 21:00	Dinner

May 9th

9:00 – 12:00	Chala Gold deposit and geology
12:00 – 13:00	Lunch
13:00 – 17:00	Ada Tepe Gold deposit
18:30 – 21:00	International Drilling Dinner

May 10th
Short Courses

7:30 – 10:00	Bus to Sofia
10:00 – 10:30	Registration at Serdika Hotel
11:00 – 16:00	Short Courses
16:00 – 16:30	Concluding remarks

Contents

Introduction

The Srednogorie metallogenic zone in Bulgaria (Fig. 1) is part of the global Tethyan-Eurasian copper belt. The Panagyuirishte ore region, the most important element of the Srednogorie metallogenic zone, contains characteristic calc-alkaline magmatism that hosts the Bulgaria's most important economic porphyry and epithermal ore deposits. Significant examples of discrete Upper Cretaceous volcano-plutonic centres with porphyry-copper deposits (Elatsite, Medet, Assarel, Tsar A ssen, Vlaykov Vruh) closely associated with intermediate- to high-sulphidation Cu-Au epithermal deposits (Chelopech, Krassen, Radka, Elshitsa) occur in the Panagyurishte ore district (Fig. 1).

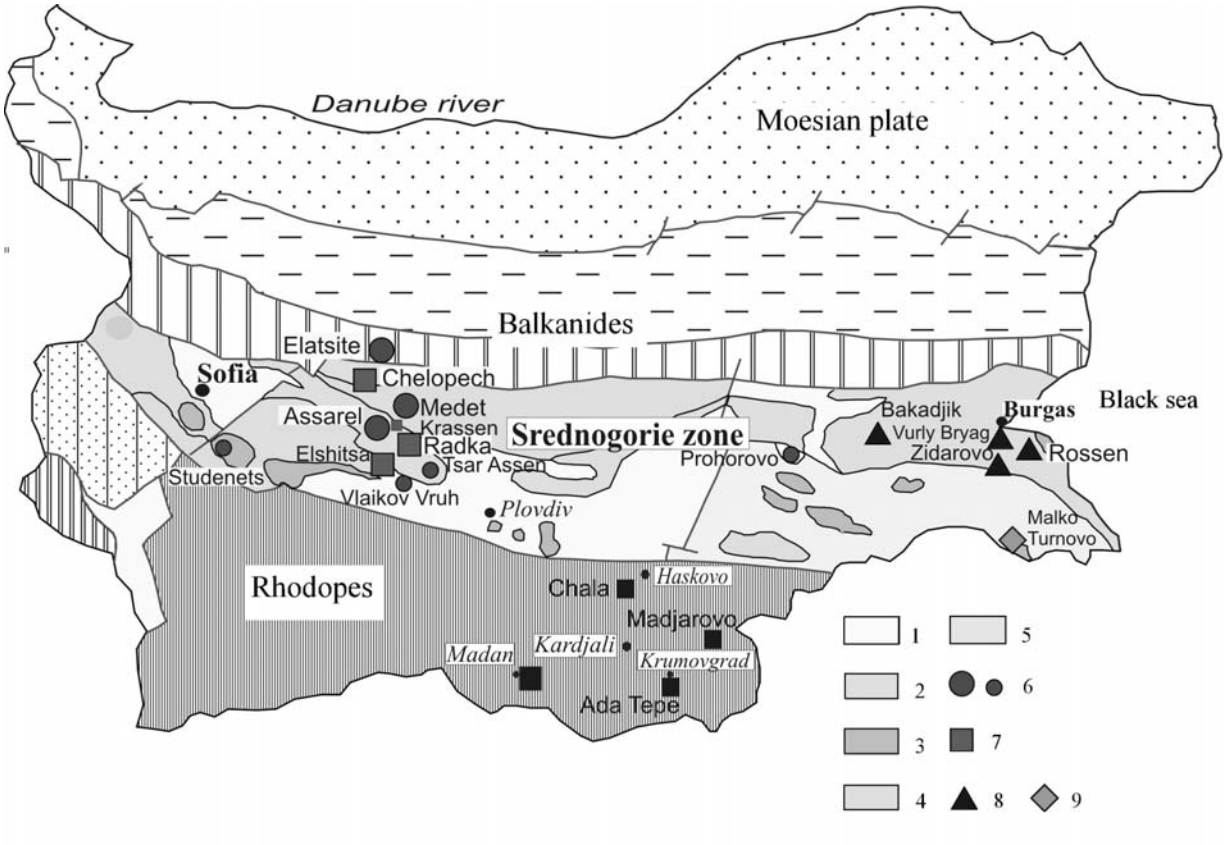

Fig. 1. Location of Cu and Au ore deposits in the Srednogorie metallogenic zone and the Rhodopes. 1 = Cenozoic sediments, 2 = Late Cretaceous volcanic rocks, 3 = Late Cretaceous intrusions, 4 = Paleozoic granites and metamorphic rocks, 5 = Paleozoic and Mesozoic metamorphic rocks, 6 = Porphyry copper deposits, 7 = Epithermal deposits, 8 = Vein copper deposits, 9 = Skarn deposits (Modified after Bogdanov and Strashimirov, 2003).

The copper ore deposits in Bulgaria have been known since ancient times. One of the oldest known copper mines in Europe, which dates from the 4th century B.C., was located in the central part of the Srednogorie metallogenic zone near the town of Stara Zagora. Copper-gold epithermal ore deposits (Radka, Elshitsa, Krassen) attracted geological studies and exploration during the twentieth century. Modern geological exploration and mining exploitation started in 1922. During the last 50 years active mining operations have been carried out in the Elatsite, Medet, Assarel, Tsar Assen, and Vlaikov Vruh porphyry deposits as well as in the Chelopech, Krassen, Elshitsa, and Radka Cu-Au epithermal deposits. Operations at present are in decline, and most of the deposit sites are being abandoned. Since 1950 more than 460 Mt of ore have been mined from these deposits, which have produced about 2 Mt Cu and 2.5 million oz of gold.

The examples described in the following pages have been chosen to emphasize different ideas concerning the geology, petrology, mineralogy, ore genesis, and metallogeny of the most important porphyry and epithermal systems in the Panagyurishte ore district as discrete evolving volcano-plutonic centers producing similar, but not identical, deposits.

During the first day of the field trip the participants will tour the Late Cretaceous Assarel and Vlaykov Vruh porphyry-copper deposits as well as the Krassen and Elashitsa epithermal Cu-Au deposits (Fig. 1), learn about local geology, see and sample host-rock alteration styles and important ore types, and discuss their genesis.

The second day of the field trip is devoted to the Tertiary LS type gold deposits Chala and Ada Tepe as a new and important targets for gold exploration and exploitation in the Eastern Rhodopes of Bulgaria.

Kamen Bogdanov, Strashimir Strashimirov, John Menzies, Sean Hasson and Dimitar Dimitrov - organizers and editors

Porphyry deposits in the central and southern part of the Panagyurishte ore region

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The Srednogorie part of the metallogenic zone in Bulgaria developed during the Mesozoic as a copper-rich, andesite-dominated island arc system (Fig. 1) that continues eastwards through Turkey to Iran. (Jankovic, 1977, 1997; Bogdanov, 1987; Dabovski et al., 1991; Heinrich and Neubauer,2002). According to Popov et al. (2000, 2002, 2003), the Panagyurishte ore region is part of the Late Cretaceous Apuseni-Banat-Timok-Srednogorie magmatic and metallogenic belt (Fig. 1).

The Panagyurishte ore district is located in a 30 x 50 km belt trending N-NW and S-SE of the town of Panagyurishte in the central Srednogorie, Bulgaria (Fig. 2). The district belongs to the Late Cretaceous Banat-Srednogorie metallogenic zone, part of the European Alpine belt (De Boorder et al., 1998; Neubauer et al., 2002). The zone (Fig.1), also known as the Banatititic magmatic and metallogenetic belt (BMMB) (Berza et al., 1998, Ciobanu et al., 2002; Heinrich and Neubauer, 2002) was formed as a result of Late Cretaceous subduction-related magmatic activity. Porphyry Cu-(Au)-(Mo) and intimately associated epithermal massive sulphides dominate in the central segments (Fig.1, Table 1)) of the belt (Ciobanu et al., 2002; Bogdanov et al., 2004), in southernmost Banat (Romania), Serbia and NW Bulgaria (Moldova Nouă in Romania, Majdanpek, Veliki Krivelj and Bor in Serbia, and Elatsite, Assarel and Chelopech in Bulgaria) Fe, Cu and Zn-Pb skarns occur mainly at the two ends of the belt (Fig.1), in Eastern Bulgaria (Malko Turnovo: Burdtzeto, Mladenovo, Velikovets) and in Romania (Apuseni Mts., N.Banat). Vein deposits are present in the easternmost districts(Fig. 1) of Yambol (Bakadjik), Burgas (Zidarovo, Vurly Bryag, Rossen).

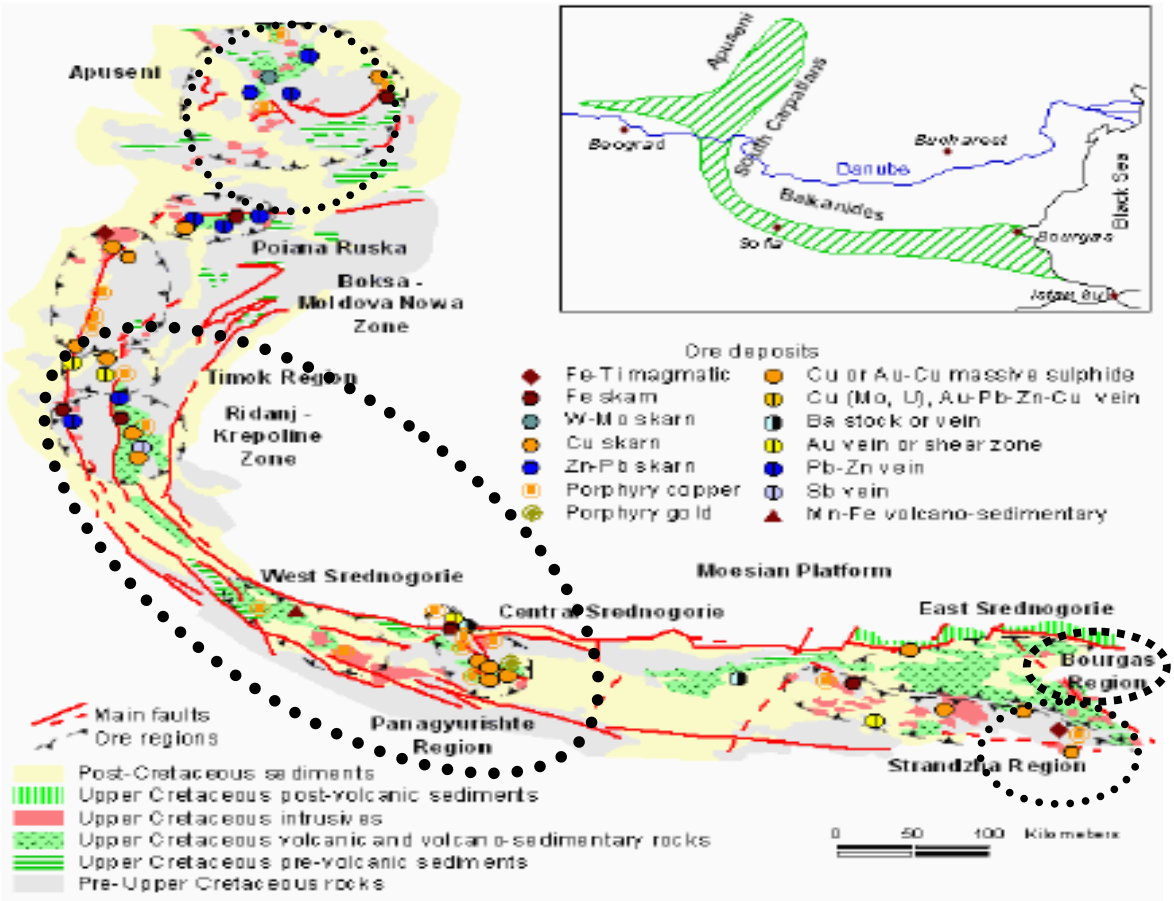

Fig.1. Late Cretaceous Apuseni-Banat-Timok-Srednogorie magmatic and metallogenic belt (After Popov et al., 2003).

Two groups of porphyry copper deposits (Fig. 2) can be distinguished in the Panagyurishte ore region (Bogdanov, 1984, 1987; Strashimirov et al., 2002, 2003; Popov et al., 2003). The first group includes deposits of intrusives within the basement rocks. Ore mineralisation and hydrothermal alteration in this group are mainly in the apical part of the intrusive bodies and partly in the basement rocks (Medet, Elatsite). The second group includes deposits developed in intrusive bodies located in effusive rocks. Hypabyssal to subvolcanic-hypabyssal porphyry intrusions controls the spatial position of the porphyry copper deposits in

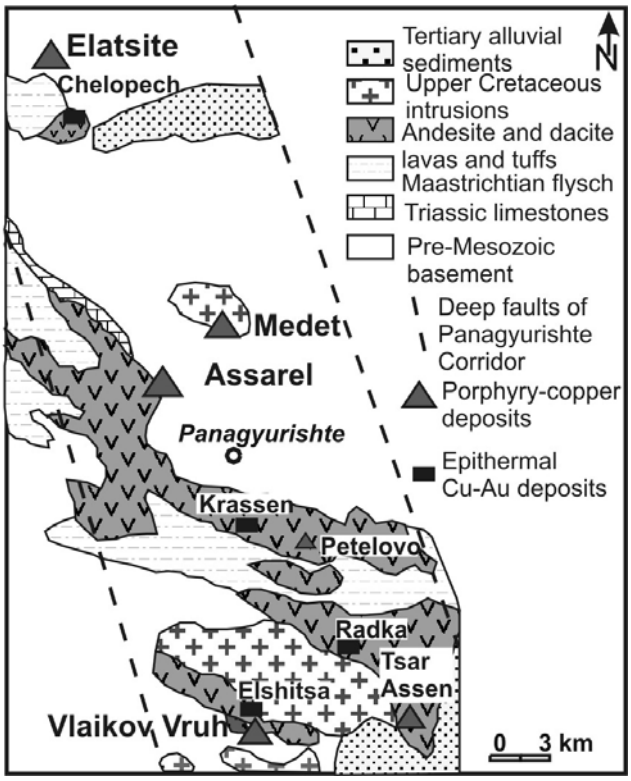

Fig. 2. Location of the porphyry copper deposit in the Panagyurishte ore region (modified after Bogdanov, 1987).

Table 1. Copper Deposits in the Panagyurishte Ore District and Their Production and Resources (data provided by the Bulgarian Ministry of Environment and Waters)

Deposit type and name	Remaining resources	Past production
Porphyry		
Assarel	254 Mt at 0.41% Cu In production since 1976	100 Mt at 0.53% Cu, trace Au
Elatsite	154 Mt at 0.33% Cu In production since 1981	165 Mt at 0.38% Cu, 0.21 g/t Au
Medet	Mined out (1964–1993)	163 Mt at 0.32% Cu, 0.1 g/t Au
Vlaikov Vruh	Mined out (1962–1979)	9.8 Mt at 0.46% Cu
Tsar Assen	Mined out (1980–1995)	6.6 Mt at 0.47% Cu
High sulphidation		
Chelopech	31 Mt at 1.39% Cu, 3.5 g/t Au In production since 1954	11.5 Mt at 1.0% Cu 3.0g/t Au
Intermediate to high sulphidation		
Krassen	Mined out (1962–1973)	0.30 Mt at 0.76% Cu
Intermediate sulphidation		
Elshitsa	Mined out (1947–1996) (1.5 Mt at 1.27% Cu)	2.5 Mt at 1.0% Cu
Radka	Mined out (1942–1997) (2.5 Mt at 0.6% Cu)	6.4 Mt at 1.0% Cu

(After Strashimirov et al., 2002; Popov et al., 2003)

both groups. In some cases they are intruded into the central parts of the volcanic structures (Assarel, Petelovo) or into volcanic slopes (Tsar Assen, Vlaikov Vruh) and in other cases they are developed in basement rocks (Elatsite) or in the apical part of the intrusives (Medet, partly Elatsite). The orebodies are cone-like or column-like, rarely of linear stockwork type.

Assarel porphyry copper deposit

The Assarel deposit is located in the central part of the Assarel volcano in an area of dense radial and concentric faulting and jointing (Figs 3, 4). The central part of the volcano is composed predominantly of lavas and brecciated lava sheets and of dominantly andesite and latite-andesite pyroclastic rocks (Fig. 3). The Assarel granodiorite porphyry is located in the center of a former stratovolcano, and it consists of two apophyses that join at depth. The northern apophysis crops out in the open pit, which is located at the side of the former hill shown on Figure 4. The ore mineralisation forms a cone whose top is inclined by 80°–85° towards the south or southwest. A horizontal cross-section of the deposit, therefore, has an ellipsoidal shape with a long axis oriented in a N-S direction. All host rocks are intensely altered, and the eastern part of the structure is uplifted due to faulting such that altered basement metamorphic rocks are now exposed at the same structural level as volcanic rocks with advanced argillic alteration (Fig. 5). This type is well developed in the Assarel deposit (Table 2) as well as in the Tsar Assen deposit and the Petelovo prospect

It is characterized by the following hydrothermal alteration: K-silicate, propylitic and advanced argillic—acid-chlorine and acid-sulphate sub-types. Sericitic alteration in these deposits is developed separately or in mixed propylitic-sericitic and sericitic-advanced argillic associations. Propylitic-argillic metasomatic rocks are found in the Asarel and Tsar Assen deposits, and moderate argillic alteration has been observed in the Petelovo prospect.

Mineralogical observations of the upper levels of the Assarel deposit revealed the following pre-ore hydrothermal alteration within sub-volcanic-hypabyssal bodies, volcanic rocks and Paleozoic granitites: propylitic, propylitic-argillic, propylitic-sericitic, sericitic, sericitic-advanced argillic and advanced argillic—acid chloride and acid-sulphate subtypes (Kanazirski

1994, 2000a, 2000b). The distinctive mineral parageneses of the various types are shown in Table 4. A typical cross-section in the central part of the deposit shown on Figure 5 illustrates the spatial distribution of the most common alteration.

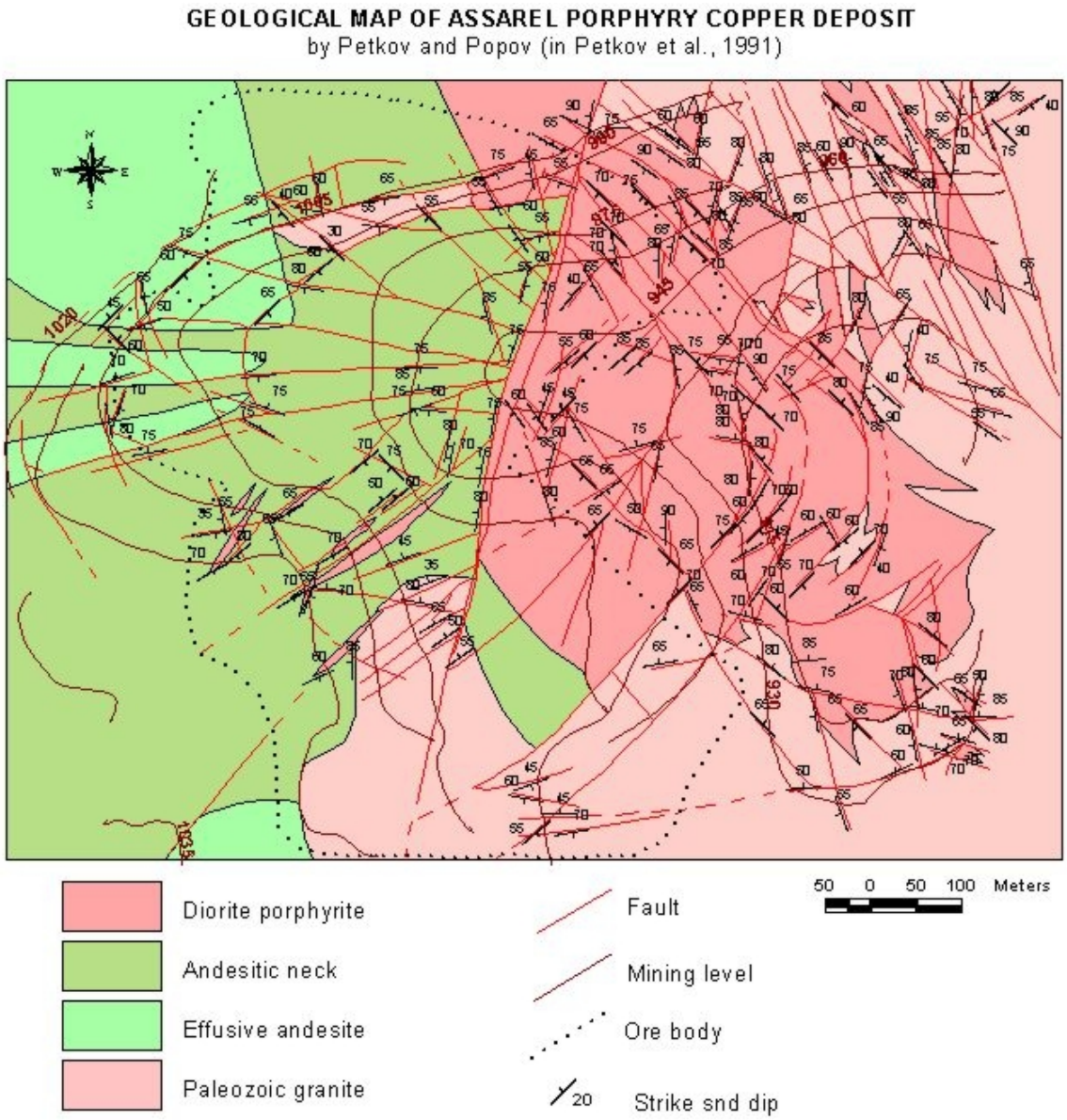

Fig. 3. Geological map of the Assarel deposit.

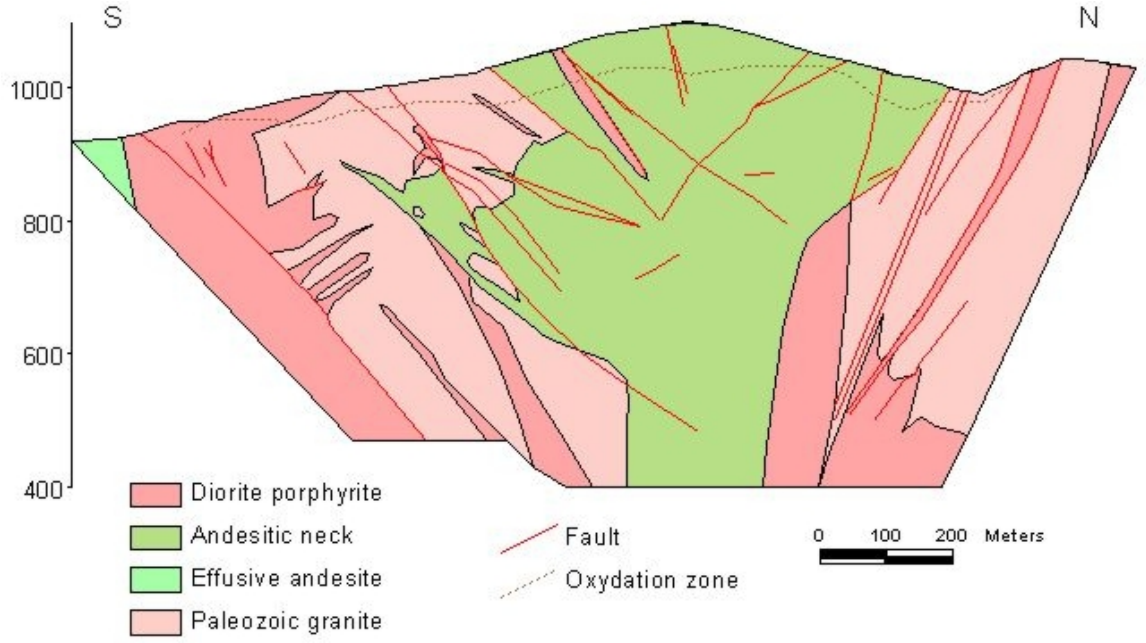

Fig. 4. Geological section of the Assarel porphyry copper deposit (based on Petkov et al., 1991).

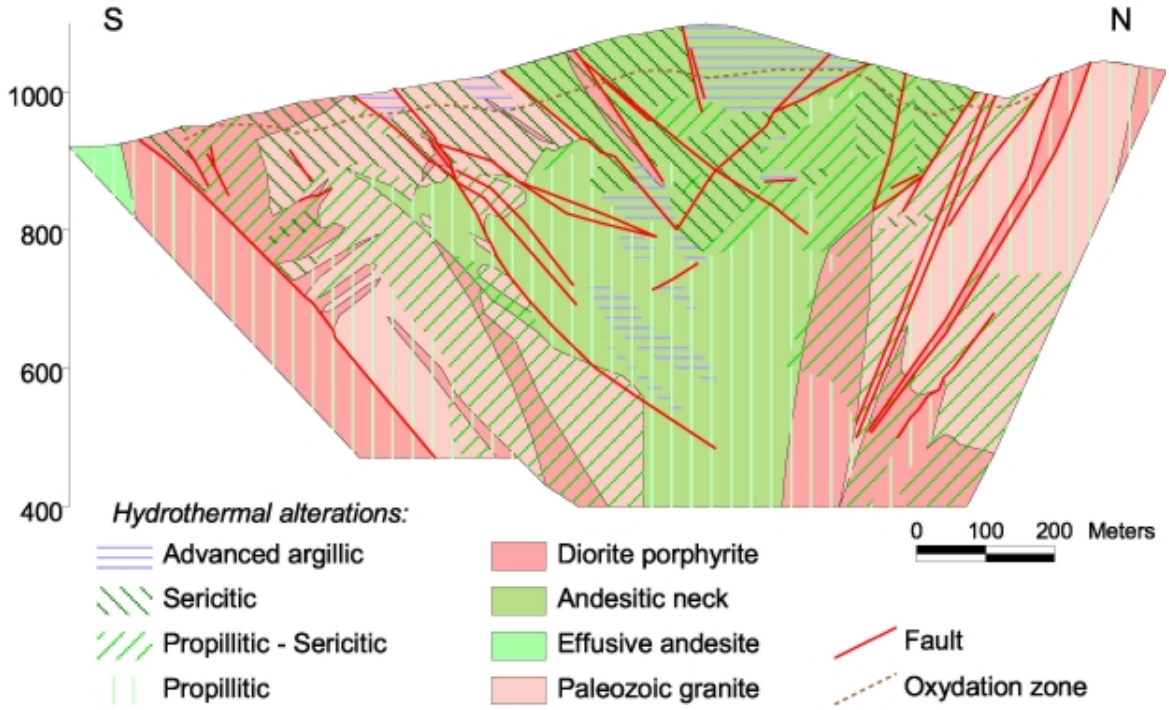

Fig. 5. Alteration types of the Assarel deposit (based on Popov et al., 1996; Strashimirov et al., 2003).

K-feldspar-biotite alteration as relicts in some areas of propylitized granodiorite porphyries and Paleozoic granitites are reported by Arnaudova et al. (1991) and demonstrate K-silicate and K-silicate-propylitic alteration, the last one sporadically found in the upper levels of the Assarel deposit (Kanazirski et al., 2000, Strashimirov et al., 2002, 2003). Epithermal sericitisation and advanced argillisation in the lithocap are seen to overprint propylitic and K-silicate alteration.

The propylitic alteration is best developed within the Upper Cretaceous volcanic rocks, subvolcanic-hypabyssal bodies and partly within the Paleozoic granitites. Propylitic-argillic and propylitic-sericitic alteration are both seen in the transition zone toward the propylitic alteration (Kanazirski 2000a, 2002). Mineral assemblages such as illite + quartz + pyrite + pyrophyllite (kaolinite) define a transitional sericitic-advanced argillic type of alteration (Table 2; Figs. 5, 6) (Kanazirski et al., 1995).

Advanced argillic alteration can be divided into two sub-types, acid-chlorine and acid-sulphate alteration. The porphyritic textures are overprinted and obscured in the acid-chlorine sub-type and the rocks are composed of pyrophyllite, quartz and pyrite ± diaspore, corundum, zunyite and kaolinite. The paragenesis kaolinite + quartz + pyrite is rare. The sequence of acid-chlorine and acid-sulphate sub-types in the Assarel deposit, as well as the ratios between alunite and kaolinite to pyrophyllite and the precipitation of alunite + kaolinite (Fig. 6) suggests changes of chlorine-acid fluids to sulphur-acid ones. Similar mineral parageneses typical for advanced argillic alteration are described in epithermal high sulphidation deposits (Silberman and Berger, 1985; Sillitoe, 1991, 1995; Eaton and Setterfield, 1993; Arribas, 1995; and others).

Formation facies analysis allows one to distinguish between alteration assemblages that are the result of epithermal advanced-argillic acid develop-ment. Thus, a kaolinite-pyrophyllite facies in a secondary quartzite formation can be separated from the quartz-alunite facies in the same formation (Table 2, Fig. 6; Kanazirski 1998; Kanazirski et al., 2000).

Mineral composition

The ore mineralogy and alteration at Assarel is particularly complex compared to the other deposits. An early quartz-magnetite-hematite association, which is typical of the porphyry copper deposits in the region, occurs only in a limited way in the Assarel deposit, and the late quartz-molybdenite association is rare (Bogdanov, 1987). The quartz-pyrite-chalcopyrite association

has a large distribution in the middle and marginal parts of the deposit. The quartz-galena-sphalerite association is rare and is found mainly in the upper part of the deposit. Galena and sphalerite are found in well-shaped veins of chalcopyrite at depth as well. Several polyelemental high-sulphidation-style assemblages are established in the upper levels (Petrunov et al., 1991). These assemblages include enargite and goldfieldite (Cu-As ± Te assemblage), colusite, As-sulvanite and sulvanite (Cu-Sn-V assemblage), aikinite and wittichenite (Cu-Bi assemblage), and hessite and tetradymite (Bi-Ag-Te assemblage) found as fine mineral inclusions in chalcopyrite. This latter assemblage is related spatially to sericitic and advanced argillic alteration of the volcanic rocks in the highest parts of the deposit. This alteration is also evidence that the porphyry copper mineralisation well developed at depth has been overprinted by high sulphidation style mineralisation in the upper parts of the system (Strashimirov et al., 2002). In contrast to the other deposits in the region, native gold is rare here, although near the contact between the zone of oxidation and the zone of the secondary enrichment chemical analyses show exceptionally high content of Au (Strashimirov, 1993)

Table 2. Mineral Assemblages and Wall-rock Alteration in the Shallow Parts of the Assarel Deposit (after Kanazirski et al., 2000; Strashimirov et al., 2002, 2003).

Wallrock alteration	**Mineral paragenesis**
	Ep + chl + ab + ksp + il + qtz + py
Propylitic	Chl + ab + ksp + il + qtz + py
	Chl + ab + il + qtz + py
Propylitic argillic	Chl + kl + ab + il + qtz + py ± ep ± ksp
	Kl + ab + il + qtz + py
Propylitic-sericitic	Chl + il + qtz + py
Sericitic	Il + qtz + py
Sericitic-advanced argillic	Il + qtz + py + prl
	Il + qtz + py + kl
Advanced argillisation	Prl + qtz + py
(acid-chloride sub-type)	Kl + qtz + py
Advanced argillisation	Alu + qtz ± prl ±py ± hem
(acid sulphate sub-type)	Alu + qtz ± kl ± py ± hem

ab = albite, alu = alunite, chl = chlorite, ep = epidote, ksp = K-feldspar, kl = kaolinite, hem = hematite, il = illite, prl = pyrophyllite, py = pyrite, qtz = quartz.

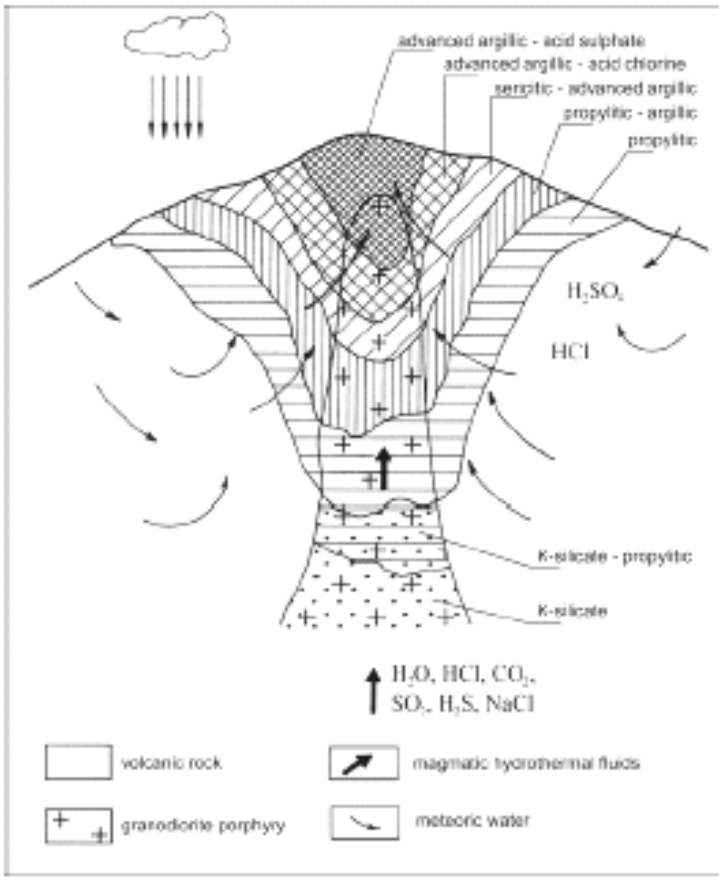

Fig. 6. Scheme of alteration zones in the Assarel porphyry copper deposit (after Kanazirski et al., 2000).

Assarel is the only major deposit in the district showing much of a secondary chalcocite and covellite supergene blanket, which is of major economic importance. The zone of supergene enrichment is a band 60–70 m thick that lies above the primary quartz-pyrite-chalcopyrite but below the zone of complete oxidation, which usually composes the first 10–15 m below the present land surface.

Medet porphyry copper deposit

Medet, discovered in 1955, is Bulgaria's first known porphyry copper deposit. The Medet deposit is located in the apical part of the Medet intrusive body of quartz-monzodiorite and granodiorite

porphyry (Fig. 7) that intruded into the N-NE part of metamorphic rocks (mainly gneisses). The most intense jointing and faulting are developed in the central and the eastern part of the intrusive body . These areas are the sites of high permeability and copper mineralisation. The ore body is an extensive pipe-shaped stockwork elongated in

a NW direction, and drilling has confirmed mineralisation to more than 1,000 m depth (Fig. 7). Ushev et al. (1962) established mineral-specific alteration zones, which can be combined into two main types: K-silicate alteration (metasomatic K-feldspar and biotite, quartz and apatite) (Fig. 14) and propylitic alteration (chlorite, epidote and carbonate). Epidotisation, chloritisation and subordinated sericitisation commonly accompanied sulphide precipitation in the Medet deposit. Sericititic alteration has a limited distribution mainly around the zone of K-silicate alteration (S. Chipchakova, 1999 personal communication). These alteration processes, in addition to precipitating chlorite and biotite, characterize propylitic wallrock alteration in the deposit contemporaneous with the precipitation of chalcopyrite and pyrite. The most likely pre-ore metasomatic rocks in this deposit are pervasive quartz-feldspar altered rocks (Fig. 7). It was concluded from wallrock alteration studies (Strashimirov et al., 2002).

Mineral Composition

The first ore-mineral association formed in the Medet porphyry copper deposit was quartz-magnetite-hematite associated with K-silicate ± propylitic alteration. The association contains Ti-bearing minerals such as rutile, ilmenite, Mn-ilmenite, pseudobrookite and davidite (Strashimirov, 1992; Strashimirov et al., 2002, 2003). The main pervasive quartz-pyrite-chalcopyrite association (Table 3) contains mineral inclusions that form specific assemblages. The Co-Ni assemblage contains carrollite, vaesite, Co- and Ni-bearing pyrites, some of them with a content of cobalt up to 17 wt % (Table 4); Cu-Sn-V (colusite and sulvanite) and Bi-Ag-Te (hessite and tetradymite) assemblages are rare as micron-sized inclusions in chalcopyrite (Table 3; Strashimirov, 1982a, b).

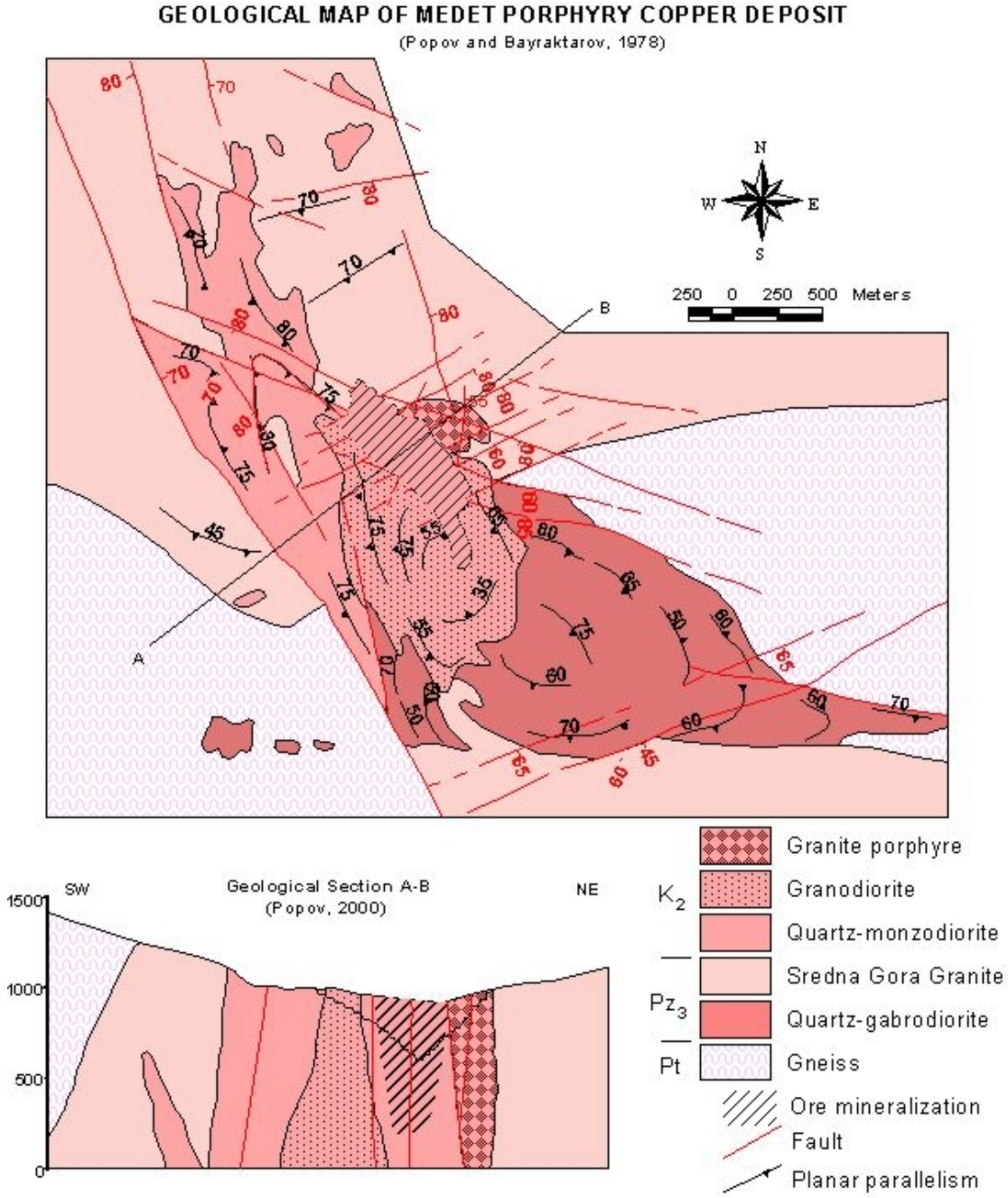

Fig. 7. Map of the Medet porphyry copper deposit (after Popov and Bayraktarov, 1978).

Table 3. Ore Mineral Associations and Geochemical Assemblages

(after Strashimirov et al., 2002, 2003)

Ore mineral association	Location and structure of ore aggregates	Specific geochemical assemblages	Characteristic minerals		
Elatsite		Assarel		Medet	
Mgt-hem ± brunt, chpy	Central parts; veinlets, aggregates, lenses	1. Fe-Ti 2. Cu-PGE-Fe-Co-Ni-Te-Bi-Se-Au-Ag 3. Ag-Se ± Te, Bi	Mgt, hem, rut, ilm Brnt, chpy, mer, ln, car, ws, mch, au Hs, cls, kz, nm, euc, bcz, te, bi	Mgt, hem, ilm - -	Mgt, hem, ilm, rut --
Qtz-py-chpy	Whole ore body; veinlets, short veins, dissem. and aggregates	1. Fe-Cu ± Mo, Au 2. Co-Ni 3. Ni-Pd-As 4.Cu-As (Te) 5.Cu-Sn-V 6. Cu-Pb-Bi 7.-Bi-Ag-Te	Py, chpy, mol, gld Car, vaes Pd-ars, pd-ramm -	Py, chpy, gld Brvt - En,gldfd, cal Colus,sulv, as-sulv Aikin,wittch	Py, chpy, mol, gld Car,vaes,co-ni-pyr Colus, sulv Hs, tetr
Qtz-mol	Inner parts; thin veinlets	Mo-Re	Qtz, mol	-	Qtz, mol
Qtz-py ±calc	Medium and outer parts; short veins	Fe ± Au	Qtz, pyr, calc, ± gld	Qtz, pyr, ± gld	Qtz, pyr, calc
Qtz-gal-sph	Marginal and upper levels; short veins	Pb-Zn-Ag ± Se	Qtz, gal, sph	Qtz, gal, sph	Qtz, gal, sph
Cov-chal (secondary)	Upper levels, (zone of secondary enrichment in Asarel)	Cu- Fe	Cov, chal, brnt	Cov, chal, brnt	Cov, chal, brnt

aikin = aikinite, brnt = bornite, bcz = bohdanowiczite, brvt = bravoite, cal = calaverite, calc = calcite, car = carrollite, chal = chalcocite, chpy = chalcopyrite, cls = clausthalite, colus = colusite, cov = covellite, en = enargite, euc = eucairite, gal = galena, Au = native gold, gldf = goldfieldite, hem = hematite, hs = hessite, ilm = ilmenite, kz = kawazulite, ln = linnaeite, mgt = magnetite,

mch = michenerite, mer = merenskyite, mol = molybdenite, nm = naumannite, Bi = native Bi, Te = native Te, Pd-ars = Pd-arsenide, Pd-ramm = Pd-rammelsbergite, py = pyrite, pyrrh = pyrrhotite, qtz = quartz, rut = rutile, sph = sphalerite, sulv = sulvanite, tetr = tetradymite, vaes = vaesite, ws = weissite, wittch = wittichenite

Table 4. Chemical Composition of Nickel Pyrite (1), Cobalt-Pyrite (2, 3, 4) and Carrolite (5, 6) from the Medet Deposit (Strashimirov, 1982a,b)

Element	1	2	3	4	5	6
Fe	38.20	33.85	30.70	28.90	1.85	2.00
Co	2.20	12.45	15.95	17.85	37.55	38.20
Ni	5.30	0.40	0.05	0.05	3.20	2.25
Cu	0.10	0.10	0.10	0.10	15.90	15.80
S	53.90	53.15	53.90	53.90	41.60	41.90
Total	99.70	99.95	100.70	100.80	100.00	100.15

Crystallochemical formulas:

1. $Fe_{0.81}Co_{0.04}Ni_{0.1}Cu_{0\cdot005}S_{2.00}$
2. $Fe_{0.73}Co_{0.25}Ni_{00.1}Cu_{0\cdot005}S_{2.00}$
3. $Fe_{0.65}Co_{0.32}Ni_{0.005}Cu_{0\cdot005}S_{2.00}$
4. $Fe_{0.63}Co_{0.36}Ni_{0.005}Cu_{0\cdot005}S_{2.00}$
5. $(Cu_{0.77}Co_{0.23})_{1.00}(Co_{1.73}Fe_{0.1}Ni_{0.17})_{1.95}S_{4.00}$
6. $(Cu_{0.76}Co_{0.24})_{1.00}(Co_{1.77}Fe_{0.11}Ni_{0.11})_{1.99}S_{4.00}$

Molybdenite occurs in this association as rare single flakes, but generally it forms discrete veinlets with quartz. Molybdenite occurs in the polymorphic modifications 2H and rarely 3R, which is characterized by a higher content of Re. The quartz-pyrite association forms well-shaped veins and veinlets in the middle part of the deposit. The quartz-galena-sphalerite association is observed rarely as small veins in the upper and marginal parts of the deposit. The end of hydrothermal activity is marked by precipitation of anhydrite-gypsum and calcite-zeolite (laumontite, heulandite, stilbite) in veinlets up to 2–3 cm wide that replace and crosscut the opaque minerals common in the upper marginal parts of the deposit. Rare malachite, azurite and cuprite could be observed in the oxidising zone, which is poorly developed. Secondary copper

minerals, such as bornite, covellite and chalcocite are rare and are found mainly in the upper part of the deposit or along faults at depth.

Vlaikov Vruh Porphyry Copper Deposit

The Vlaikov Vruh porphyry copper deposit (Fig. 8) is located in the central part of Elshitsa ore field, about 1.5 km south of Elshitsa village and about 80 km SE of Sofia city (Fig. 2). It covers an area of about 0.5 km diameter. The deposit was open-pit mined from 1962 to 1979. During that time, 9,793,400 t copper ore with 0.46% average copper content was extracted (Milev et al., 1996). Resources of 22,700 t copper ore with 0.32% average copper contents still remain in the deposit. The porphyry-copper mineralisation is hosted in porphyry granodiorite to quartz diorite, which is intruded along the contact of Upper Cretaceous andesites, dacites, breccias and tuffs and in the pre-Mesozoic metamorphic and granitic basement (Figs. 8, 9). The intrusion extends E-W and is intersected by north-trending dacitic dykes. The geology of the Vlaikov Vruh deposit and the entire Elshitsa ore field is controlled by the setting and evolution of the Elshitsa volcano-intrusive
complex (Bogdanov et al., 1970, 1972; Popov et al., 2000c). The Elshitsa effusive suite, numerous volcano-tectonic faults and later minor intrusives within the area of deposit compose this complex. The Vlaikov Vruh deposit is related to the granodiorite porphyry intrusion, which cuts the effusive rocks from the southern slope of Elshitsa stratovolcano as well as the basement rocks (Fig 8).

The pre-Upper Cretaceous basement consists of Precambrian(?) muscovite-biotite and biotite gneisses. Garnet-two-mica, granitized biotite, muscovite and aplitic gneisses as well as layers from biotite and two-mica gneissic schists and schists are rarely observed. These rocks are assigned to the Pre-Rhodopian Supergroup with probable Archaean-Lower Proterozoic age (Katskov and Iliev, 1993). The Elshitsa effusive suite contains lava flows, lava-breccias, agglomerate, lapilli and rarely ash tuffs with 100°–130° strikes and 10°–30° N-NE dips overlying the highly

metamorphosed basement rocks. Two sequences, andesitic (lower) and dacitic (upper), are distinguished in the suite (Boyadjiev and Chipchakova, 1963). The subvolcanic intrusions are mainly dacitic but rarely andesitic in composition. They are intruded mostly along E-SE faults

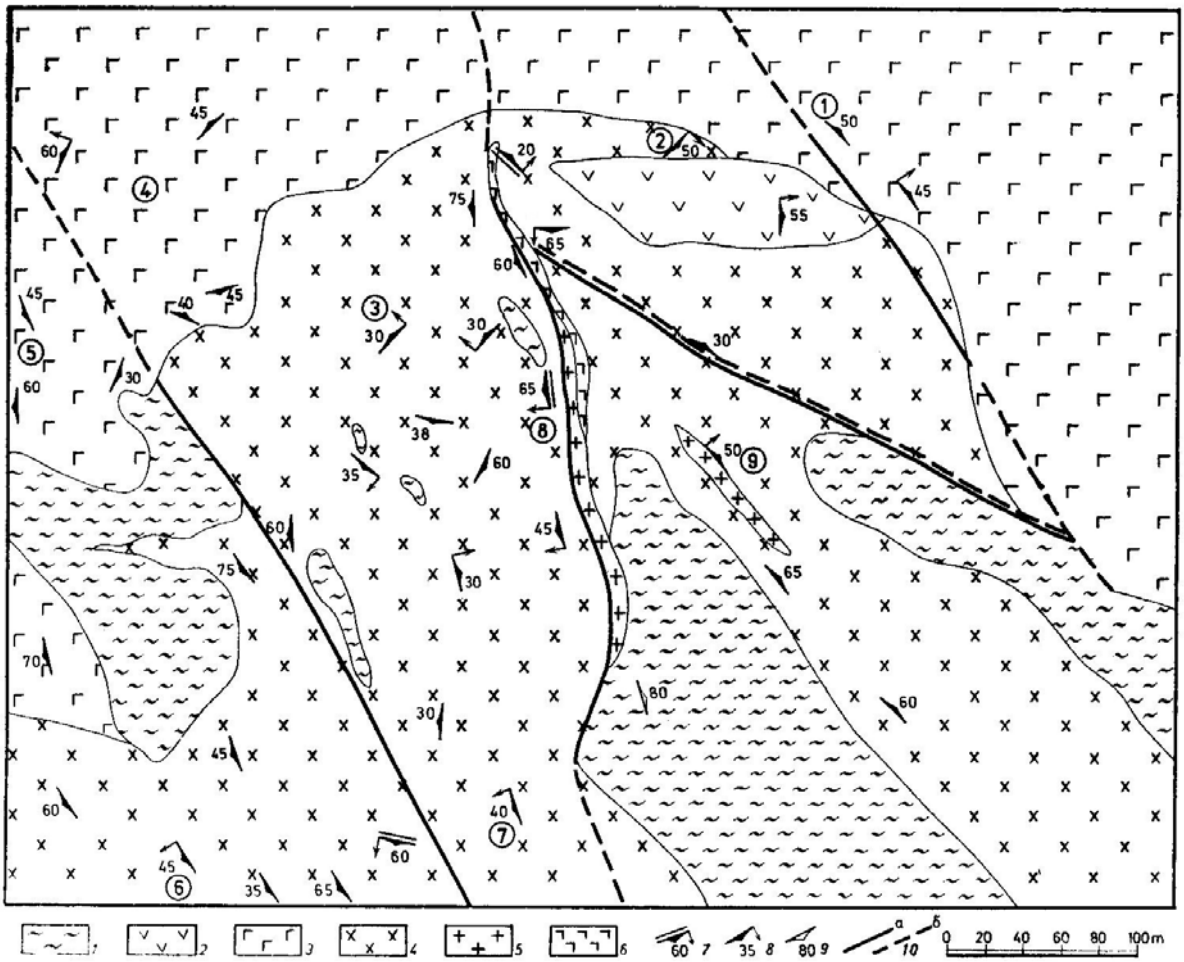

Fig. 8. Geological map of the Vlaykov Vruh porphyry copper deposit (after Bogdanov et al., 1972). 1 = gneisses; 2 = andesite; 3 = dacite; 4 = granodiorite; 5 = granodiorite porphyry dykes; 6 = dacite dykes; 7 =lineation; 8 = schistosity ; 9 = magmatic foliation; 10 = faults.

and less along N-NW and E-NE faults in both the northern and the southern flanks of the deposit. The Vlaikov Vruh intrusion is subvolcanic to hypabyssal and consists of porphyry granodiorite (with transitions to porphyry quartz-monzodiorite, porphyry

granite and porphyritic plagiogranite) with dacitic enclaves in the poorly crystallized parts around the contacts (Figs. 8, 9). Xenoliths from the metamorphic and rarely from the volcanic rocks (up to 170 x 420 mm in size) have also been observed. The major axis of the intrusion trends 115°–120°, its length is over 2 km and width is 100–150 m in the western part to 750–800 m in the eastern part. Meandering contacts and numerous apophyses penetrated into the host rocks are typical of the intrusive. The late dacitic dykes with N-NW and E-SE trends crosscut all rock types including the altered propylitic rocks and the ore mineralization.

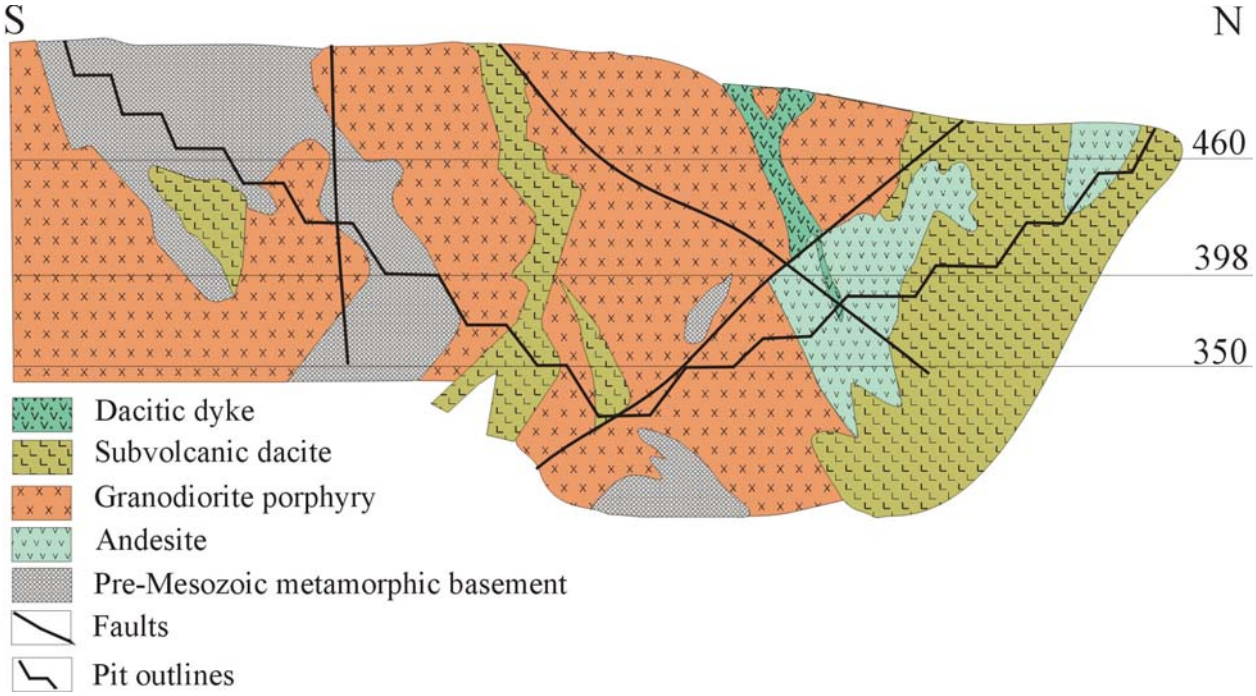

Fig. 9. Cross-section of the Vlaykov Vruh porphyry copper deposit (modified after Popov et al., 2000c). 1 = dacitic dyke; 2 =subvolcanic dacite; 3 = porphyry granodiorite; 4 = pre-Mesozoic basement; 5 = primary Cu-Mo mineralisation; 6 = zone of secondary Cu-sulphide enrichment.

Longitudinal E-SE (100°–135°) and diagonal N-NW (330°–350°) faults (Figs. 8, 9) are developed in the area of the Vlaikov Vruh deposit as an important element of the Elshitsa volcano-intrusive complex. The Vlaikov Vruh fault and several smaller sub-parallel structures represent the E-SE trending faults (100°–135°). The longitudinal faults are characterized by steep sub-vertical to north dips. Normal and strike-slip

movements and uplift of the southern blocks occurred along these faults during volcano-tectonic deformation. N-NW–trending dextral strike-slip faults (330°–350°) belonging to the Panagyurishte fault zone are characteristic of the southern margin of the Vlaikov Vruh open pit. An almost meridional fault hosts granodiorite-porphyritic and dacitic dykes (Figs. 8, 9) The porphyry Cu vein-like and disseminated ore mineralisation with minor molybdenite is hosted by the porphyry granodiorite and partly in the basement metamorphic and the dacite and andesite volcanic rocks. K-silicate, sericitic (phyllic) and propylitic pre-ore hydrothermal alteration have been recognized in the deposit (Bogdanov, 1987; Tsonev et al., 2000). Four vertically elongated stockwork ore bodies can be distinguished in the deeper parts, coalescing into a single ore body in the upper parts of the deposit. The main ore body is oxidized to a depth of some 10–20 m, characterized by the development of malachite-azurite ores, below which is a zone of secondary enrichment, up to 40–50 m in depth, which is characterized by bornite-chalcocite-covellite ores. The tectonic jointing and faulting occurred after solidification of the intrusive controlled the development and localization of ore mineralization. Volcano-tectonic faults were reactivated along the E-SE trends as well as along the diagonal NE and N-NW trends (Figs. 8, 9). The jointing is expressed by reactivation of the primary sub-parallel and branch joints around the faults. Part of the new small faults is sub-parallel to the primary bedding joints. The jointing and faulting determines the development of economically significant minerali-zation mainly within the intrusive bodies, due to their greater brittleness.

Mineral Composition

The porphyry Cu vein-like and disseminated ore mineralisation with minor molybdenite was deposited at a very early stage in the evolution of the hydrothermal system. Pyrite-chalcopyrite and molybdenite mineralization occurs in thin veinlets and in veins up to 2 cm wide, crosscutting late-magmatic aplite-pegmatite veins and the granodiorite. In addition, the veinlets contain quartz, minor amounts of titanite, rutile, and isolated inclusions of pyrrhotite.

The oxidizing zone is well expressed and is up to 10–20 m thick, and it contains Fe-hydroxides and minor amounts of cuprite, native copper, malachite, chrysocolla and azurite. The secondary enrichment zone built up an almost-horizontal zone 300 x 30 m in the central part of the deposit, which consists mainly of chalcocite with minor bornite and covellite (Bogdanov, 1987). According to Kouzmanov et al. (2001) the early hydrothermal fluids are represented by high-temperature (325°–370°C) and high-salinity (up to 48 wt % NaCl equiv) liquid-rich, and medium- to high-temperature (260°–310°C) and low-salinity (4.7–5.9 wt % NaCl equiv) fluid inclusions with variable liquid/vapour ratios. In addition the high-salinity fluid inclusions usually contain numerous solid phases, such as NaCl, anhydrite, chalcopyrite, hematite and two unidentified solids. The fluid inclusions studied are interpreted to represent an orthomagmatic fluid that boiled, causing sulphide precipitation. Preliminary results from Re-Os dating on molybdenite with relatively low Re content (0.02–0.96 wt %) (Kouzmanov, 2001) suggest that the mineralizing process took place about 82 Ma.

Features of the porphyry copper deposits of the Panagyurishte ore region

Similarities and differences in mineral associations and fluid inclusions from the hydrothermal systems in porphyry copper deposits from the Panagyurishte region of the central Srednogorie zone reflect the geologic position of ore mineralisation within the framework of the Upper Cretaceous volcanic-intrusive complexes.

Although depths and fluid pressures have not been quantified at this stage, the deposits may together represent a continuum from relatively deep basement-hosted deposits centered on intrusive stocks (Elatsite, Medet) to rather shallower and lower-temperature hydrothermal systems associated with subvolcanic stocks intruding their own volcanic superstructures (Assarel). The porphyry style of wallrock alteration from these deposits contains K-silicate and propylitic alteration as an early stage of the hydrothermal-metasomatic processes (Table 5, 6). The outer parts of the deposits are generally

Table 5

Table 2. Ore Mineral Associations and Geochemical Assemblages (after Strashimirov et al., 2002)

Ore mineral association	Location and structure of ore aggregates	Specific geochemical assemblages	Characteristic minerals		
			Elatsite	Assarel	Medet
Mgt-hem ± brunt, chpy	Central parts; veinlets, aggregates, lenses	1. Fe-Ti	Mgt, hem, rut, ilm	Mgt, hem, ilm	Mgt, hem, ilm, rut
		2. Cu-PGE-Fe-Co-Ni-Te-Bi-Se-Au-Ag	Brnt, chpy, mer, ln, car, ws, mch, au	-	--
		3. Ag-Se ± Te, Bi	Hs, cis, kz, nm, euc, bcz, te, bi	-	
Qtz-py-chpy	Whole ore body; veinlets, short veins, dissem. and aggregates	1. Fe-Cu ± Mo, Au	Py, chpy, mol, gld	Py, chpy, gld	Py, chpy, mol, gld
		2. Co-Ni	Car, vaes	Brvt	Car, vaes, co-ni-pyr
		3. Ni-Pd-As	Pd-ars, pd-ramm	-	-
		4.Cu-As (Te)	-	En, gldfd, cal	-
		5.Cu-Sn-V	-	Colus, sulv, as-sulv	Colus, sulv
		6. Cu-Pb-Bi	-	Alkin, wittch	-
		7.-Bi-Ag-Te	-	-	Hs, tetr
Qtz-mol	Inner parts; thin veinlets	Mo-Re	Qtz, mol	-	Qtz, mol
Qtz-py ±calc	Medium and outer parts; short veins	Fe ± Au	Qtz, pyr, calc, ± gld	Qtz, pyr, ± gld	Qtz, pyr, calc
Qtz-gal-sph	Marginal and upper levels; short veins	Pb-Zn-Ag ± Se	Qtz, gal, sph	Qtz, gal, sph	Qtz, gal, sph
Cov-chal (secondary)	Upper levels, (zone of secondary enrichment in Asarel)	Cu- Fe	Cov, chal, brnt	Cov, chal, brnt	Cov, chal, brnt

alkin = alkinite, brnt = bornite, bcz = bohdanowiczite, brvt = bravoite, cal = calaverite, calc = calcite, car = carrollite, chal = chalcocite, chpy = chalcopyrite, cis = clausthalite, colus = colusite, cov = covellite, en = enargite, euc = eucairite, gal = galena, Au = native gold, gldf = goldfieldite, hem = hematite, hs = hessite, ilm = ilmenite, kz = kawazulite, ln = linnaeite, mgt = magnetite, mch = michenerite, mer = merenskyite, mol = molybdenite, nm = naumannite, Bi = native Bi, Te = native Te, Pd-ars = Pd-arsenide, Pd-ramm = Pd-rammelsbergite, py = pyrite, pyrrh = pyrrhotite, qtz = quartz, rut = rutile, sph = sphalerite, sulv = sulvanite, tetr = tetradymite, vaes = vaesite, ws = weissite, wittch = wittichenite

affected by propylitic alteration developed proximally to a K-silicate zone (Medet deposit), a sericitic zone (Elatsite deposit), or a sericite-advanced argillic alteration zone (Assarel deposit). The zone of K-silicate alteration in the Elatsite deposit is

replaced at the upper levels by a zone of K-silicate-sericitic alteration, where the main sulphide mineralisation and quartz-pyrite veins are developed (Table 5). Sericitic and advanced argillic assemblages (acid-chlorine and acid-sulphate sub-types) could be developed at the upper levels and are representatives of an epithermal style of alteration (e.g., Assarel). This type of alteration overprints the K-silicate and propylitic alteration as the second stage of wallrock alteration. This stage is only weakly expressed in the Medet deposit due to the deeper erosion level of this deposit. Apart from differences of the erosion level, the differences in the types of the wallrock alteration are probably due to variable proportions of vapour and brine fluids derived from a magmatic source and low-salinity fluids of meteoric origin (Table 6). However, more data have to be collected to apply precise modeling of the development of these systems.

The characteristic features of the ore mineralisation common in all three deposits are (1) the appearance of Fe-Ti-oxide mineralisation at the beginning of the ore-forming process, (2) the wide distribution of pyrite-chalcopyrite association as the main economic stage, (3) and the presence of quartz-molybdenite, quartz-pyrite and quartz-galena-sphalerite veins at the later stages of the development of the systems (Table 5, 6). The most significant differences among the deposits are the presence of PGE and gold mineralisation in the Elatsite deposit, as well as the occurrence of an epithermal style of mineralisation and the very rare distribution of molybdenite in the Assarel deposit. These characteristics indicate differences of the primary source of the ore elements. PGE mineralisation and Co-Ni assemblages found in the Elatsite deposit and Co-Ni assemblage in the Medet deposit suggest probable participation of fluids influenced by

Table 6

Table 7. Temperature of Homogenization, Composition and Salinity in the Porphyry Copper Deposits Elatsite, Medet and Assarel (data from Strashimirov et al., 2002; Kehayov et al., 2003; Tarkian et al., 2003)

Mineral association	Fluid inclusion data T_h (°C) / (wt % NaCl equiv)		
	Elatsite	Medet	Assarel
Quartz-K-feldspar	>500 n.d.	>500 n.d.	n.d. n.d.
Quartz-magnetite-hematite (± born, chlpy, pyrrh)	600–450 H_2O-NaCl ± $FeCl_2$ ± $CaCl_2$ 64–42	400–380 H_2O-NaCl ± $FeCl_2$ 20–12	n.d. n.d.
Quartz-pyrite- chalcopyrite	450–330 H_2O- NaCl-KCl to H_2O- NaCl 50–44	390–320 H_2O-NaCl-KCl to H_2O-NaCl	310–290 n.d.
Quartz-molybdenite Quartz-pyrite	360–310 300–260 43–40	330–300 310–280	not found 230–215
Quartz-galena-sphalerite	240–200 25–20	280–240	195–150

* n. d. = no data

mafic/ultramafic materials. Enargite and numerous rare minerals including tellurides and selenides occur at Assarel, emphasizing the nature of this deposit as transitional to the high-sulphidation epithermal environment. Major pyrite-rich epithermal "massive-sulphide" Cu-Au deposits are spatially associated within a few kilometers of the large and some of the smaller porphyry-copper deposits in the Panagyurishte ore district. They are of medium- to high-sulphidation style and have a similarly complex element association with abundant arsenic, bismuth and other sulphides and tellurides (Cook et al., 2002; Kouzmanov et al., 2002, 2003; Bogdanov et al., 2004). Heinrich et al (1999) suggested that in some cases this could be an indication of a relationship-between magmatic vapour conden-sates from subjected porphyry-copper deposits and epithermal fluids forming high-sulphidation deposits. It is assumed that in the Medet

and Elatsite deposits only limited participation of meteoric waters occurred in the initial stages. In contrast, the shallower volcanic level of the Assarel system facilitated intense re-working of the host rocks in an environment that was more open to the incursion of meteoric water. Interactions of low- and high-salinity magmatic fluids with meteoric waters within a composite cross-section, extending from basal intrusives up into to the subvolcanic domain, might explain the close spatial relationships between porphyry copper and intermediate- to high-sulphidation epithermal styles of mineralisation, which are a characteristic of the Panagyurishte district and of the Balkan-Carpathian belt in general.

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Ore geology and mineralogy of the Cu-Au epithermal deposits in the southern part of the Panagyurishte ore region

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The Panagyurishte ore district is located in a 30 x 50 km belt trending N-NW to S-SE, including the town of Panagyurishte in Central Srednogorie, Bulgaria (Fig.1). The district belongs to the Late Cretaceous Banat-Srednogorie metallogenic zone, part of the Alpine-Balkan-Carpathian-Dinaride (ABCD) belt *(Heinrich* and *Neubauer*, 2002). The Srednogorie part of the ABCD belt in Bulgaria, developed during the Mesozoic as a copper-rich, andesite-dominated island arc system (Fig. 1) that continues eastwards through Turkey to Iran (*Jankovic* 1977; *Bogdanov* 1987; *Dabovski* et al., 1991; *Heinrich* and *Neubauer*, 2002).

A series of volcanic rock-hosted sulphide ore deposits (e.g., Radka, Elshitsa and Krassen) related to Late Cretaceous andesite-dacite volcanic activity are located in the southern part of the Panagyurishte district (Fig.1). They are spatially associated with small porphyry copper ore deposits (Vlaikov Vruh, Tsar Assen, Petelovo) hosted by co-magmatic subvolcanic monzodiorite, granodiorite and quartz diorite porphyritic intrusions.

Two main types of ore bodies are characteristic of the volcanic rock-hosted sulphide deposits: early massive pyrite ore bodies and late Cu-Au sulphide ore bodies. The massive structures of the early pyrite ores and the presence of pyrite laminations in the host dacite tuffs at Radka, Elshitsa and Krassen have been interpreted as possibly due to syngenetic VMS deposition coeval with dacitic volcanism (*Bogdanov* 1984, 1987; *Bogdanov* et al., 1997, 2005). However the VMS-style massive sulphide and porphyry copper deposits have been considered as incompatible ore types, characteristic of discrete tectono-magmatic settings (*Sillitoe*, 1999). At the same time, characteristic features (Table 1) such as adularia-sericite and advanced argillic alteration styles, the steep fault-controlled ore bodies (including the early massive pyrite ore bodies), the abundance of enargite, bornite and chalcocite in the late Cu-Au ores provide good reasons to regard these deposits as the analogues of enargite-bearing massive sulphide deposits, positioned high and/or late in porphyry copper systems (*Sillitoe*, 1983; *Sillitoe* et al., 1996). Such deposits have more recently been described as epithermal high (alunite-kaolinite) and low (adularia-sericite) sulphidation deposits (*Heald* et al., 1987; *Hedenquist* et al., 1996). This classification based on

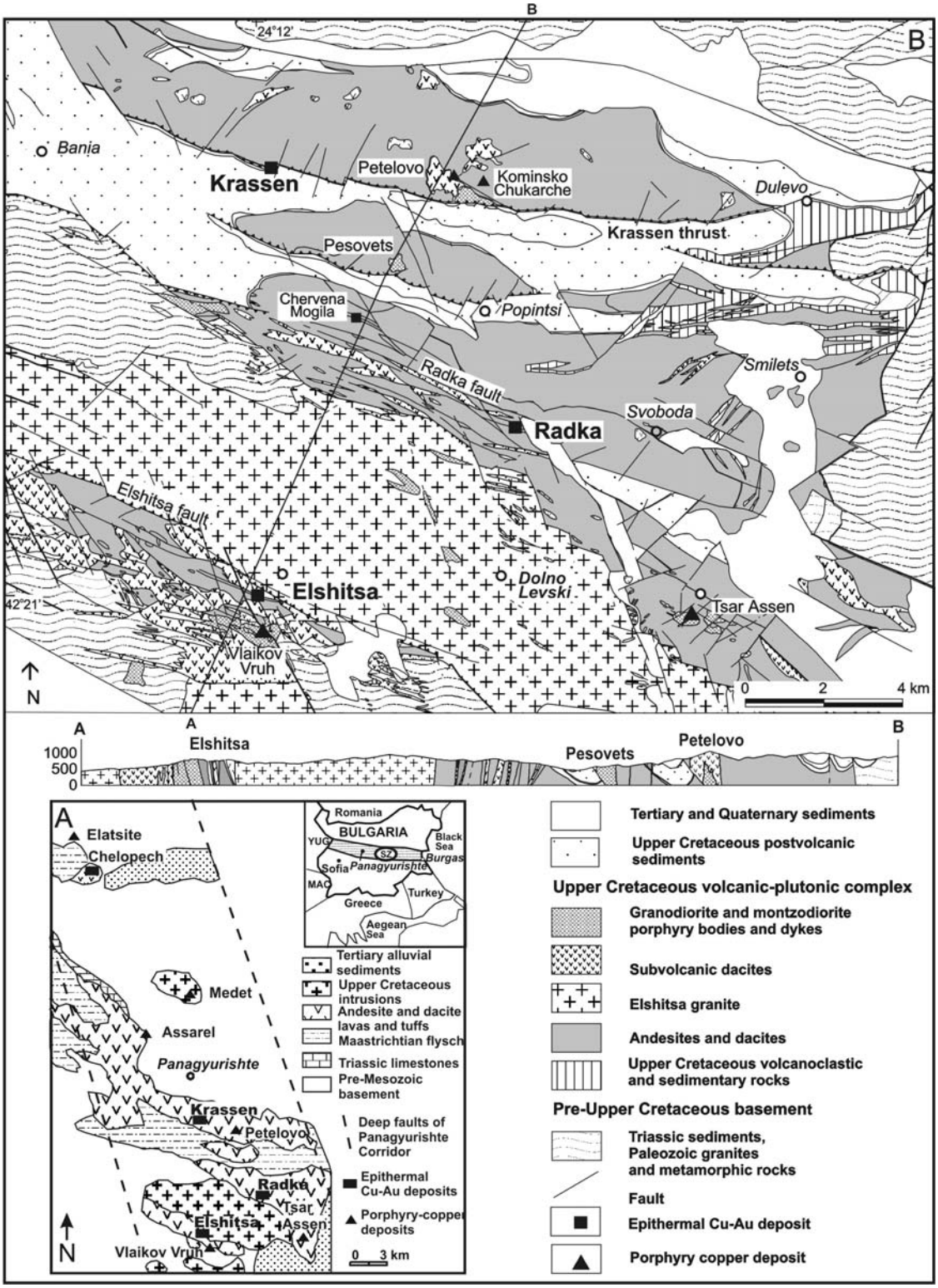

Figure. 1 **A**: Scheme of the Panagyurishte ore region (after *Bogdanov,* 1987); MP-Moesian plate; SZ-Srednogorie zone; RM-Rhodopian massif; **B**: Geological map of the southern part of the Panagyurishte ore region (modified after *Popov* and *Popov*, 2000 and Bogdanov and Popov, 2003).

oxidation state of sulphur has more recently been expanded (Hedenquist et al., 2000; Sillitoe and Hedenquist, 2003) to include an intermediate sulphidation division that is affiliated with some high-sulphidation deposits in volcanic arcs, a distinctly different volcano tectonic setting from most low sulphidation deposits.

The mineral deposits in the Srednogorie zone have been mined since the 4th century BC (*Bogdanov*, 1987). The first documented exploitation for copper in the areas of Krassen and Elshitsa started in 1922. The Radka deposit was discovered six years later, but active mining began in 1936 under the French "Companie Orient". The Krassen, Elshitsa and Radka deposits, together with the Vlaikov Vruh and Tsar Assen porphyry copper deposits, were mined all. Between 1942-1995 the epithermal deposits in Panagyurishte district (Table 1) produced 9.6 Mt of copper ores, 2.1 Mt pyrite ores and 96 000 t of copper and 665 185 t of sulphur (*Milev* et al., 1996). There is no data about gold production during the above-mentioned period, but based on research by *Milev* et al. (1996), we estimate that quantity to 7.6 tons.

Table 1. Features of the epithermal deposits of the southern part of the Panagyurishte ore region

Deposit	Ore host rocks	Host rock alteration	Ore body types	Main ore minerals	Copper ore production (Mt)	*Cu (%)*	Pyrite ore production (Mt)
Elshitsa	Dacite lavas and tuffs	Quartz-sericite ± illite Albite-chlorite-sericite Quartz-diaspore Propylitic	Stocks, lenses, lenticular bodies, veinlet-disseminated ore bodies	Pyrite, chalcopyrite Tennantite,Galena, Sphalerite, Gold	2.5 (1947–1995)	1.03	1.82 (1941–1990)
Radka	Dacite lavas and tuffs	Quartz-sericite ± illite Adularia-sericite Propylitic quartz-kaolinite Quartz-diaspore	Lenses,stocks, columnar and lenticular bodies, pipe-like,veinlet-disseminated ore bodies	Pyrite, Chalcopyrite Bornite;Tennantite, chalcocite Galena, Sphalerite, Gold	6.8 (1942–1995)	1.06	0.27 (1946–1973)
Krassen	Andesite lavas and tuffs	Quartz-sericite ± illite Quartz-kaolinite-dickite Propylitic	Lenses, lenticular ore bodies, veinlet-disseminated ore bodies	Pyrite, enargite Bornite Chalcopyrite Gold	0.30 (1962–1973)	0.76	0.003 (1965)

Geological setting

The Panagyurishte ore district consists of pre- Upper Cretaceous metamorphic crystalline basement, Triassic sedimentary rocks, Turonian-Lower Senonian volcano-sedimentary rocks, and Upper Senonian, Tertiary and Quaternary sedimentary rock complexes (*Strashimirov* and *Popov*, 2000).

The *pre-Upper Cretaceous rocks* comprise metamorphic basement of Balkanide type (two-mica gneisses, mica schists and orthoamphibolites), granites of Paleozoic age, and Triassic sandstones and dolomites (Fig. 1B). The basement rocks are overlain by Upper Cretaceous rocks, subdivided

into three distinct volcanic and sedimentary complexes of Turonian, Lower Senonian and Upper Senonian age.

The Turonian terrigenous complex is 150 to 400 m thick and consists of breccia, conglomerates, coal-bearing slates and sandstones, lying discordantly above the older rocks.

The Upper Cretaceous (Lower Senonian) volcano-plutonic complex is composed of calc-alkaline to shoshonitic volcanic and rare sedimentary rocks and was formed in several extrusive centres. The Krassen-Petelovo (andesite), Svoboda (latite), Elshitsa (andesite, dacite) and Pesovets (andesite-basalt) volcanic suites (Fig. 1) are associated with numerous comagmatic dacite and porphyritic granodiorite intrusions. The Lower Senonian volcano-plutonic complex has a multistage and explosive character and hosts both porphyry and epithermal ores.

The Upper Senonian postvolcanic sedimentary complex is represented by the Santonian-Campanian marlstones, sandstones and conglomerates as well as by the 500 to 700 m thick Campanian-Maastrichtian carbonaceous flysch. The *Tertiary and Quaternary sediments* consist of Paleogene conglomerates, Pliocene breccia and conglomerates, sandstones and clays; and Quaternary gravels, sands and clays covering part of the pre-Cenozoic sequence (Fig.1B).

All the volcano-plutonic complexes associated with the ore deposits are composed of a volcanic edifice and co-magmatic sub-volcanic rocks, intrusions and dykes. The volcano-plutonic complexes formation include: *1) volcanic; 2) plutonic; 3) sub-volcanic; and 4) dyke stages* of magmatic activity (Bogdanov, 1987).

Pyroxene-amphibole andesite lavas of the *volcanic stage* are dominant in the central and northern parts of the Panagyurishte ore region. In the southern parts, however, dacitic lavas, agglomerate and ash tuffs and sub-volcanic dacites are more abundant (*Bogdanov*, 1987). The andesite lavas are intercalated with dacitic agglomerate and ash tuffs. The explosive breccia facies constitutes around one third of the total volume of the dacitic volcanism that occupies zones both, NE and SW of the Elshitsa pluton (Fig. 1B). The Medet granodiorite-monzodiorite and Elshitsa granite plutons were intruded in uplifted blocks, of gneiss and schist of the pre-Mesozoic crystalline basement during the *plutonic stage*. Small stocks and dykes of sub-volcanic dacite and porphyritic granodiorite intruded the W-NW-trending fault zones (Fig. 1B). Dips to the central part of the Elshitsa pluton are characteristic for dykes of the *sub-volcanic stage*. The diorite-porphyry dykes in the apical part of the Medet pluton and in the northern part of Elatsite (Fig. 1A) were also linked to the sub-volcanic stage of the magmatic activity (*Bogdanov*, 1987; *Strashimirov* and *Popov*, 2000). Small dykes and basalt, trachybasalt and trachyandesite flows are characteristic of the *dyke stage*. The andesite and dacite rocks developed along the W-NW trending Elshitsa, Radka and Krassen-Petelovo volcanic zones (Fig. 1B). Ages of the main magmatic stages based on K/Ar dating are as follows: volcanic (92-87Ma), plutonic (88-82Ma), sub-volcanic (88-74Ma) and dyke (74-67Ma), (*Bogdanov*, 1987;

Lilov and *Chipchakova*, 1999). Based on U-Pb zircon dating, *Peytcheva* et al., (2001, 2003) provided ages between 81.2 +0.5/-0.7 and 86.62 ± 0.02 Ma for the Elshitsa granite and 86.11 ±0.23Ma for the Elshitsa subvolcanic dacites. A preliminary $^{40}Ar/^{39}Ar$ amphibole age of 85.70 ± 0.35Ma for the coarse-grained granodiorite of the Medet pluton was obtained by *Handler* et al., (2002). This ages dates span of about 25 m.y. suggesting magmatic activity was punctuated, changing character and relatively long lived.

Most of the porphyry-epithermal systems are related to positive gravity anomalies located along the deep sub-meridional fault structure that limit the Panagyurishte structural corridor (Fig. 1A). Aeromagnetically the centers are positive anomalies although further detailed data publication is required. Intersections between the NW-trending (310-320°) faults forming the volcano-tectonic depressions with the sub-meridional faults are regarded as important magmatic and ore-controlling structures (*Bogdanov*, 1987; *Strashimirov* and *Popov*, 2000). The formation of discrete porphyry-epithermal coeval mineralised centres in volcano-tectonic depressions can be interpreted as deep, narrow pull-apart basins produced by strike-slip faults (*Ivanov*, 2005). The transpressional tectonic regime at the end of the Late Cretaceous resulted in the deformation and transformation of the whole magmatic and sedimentary complex together with the crystalline basement and development of fold structures with NW and E-W directions of the fold-axes and north trending reverse faults (*Ivanov*, 2005). As a final result the whole system is uplifted and the shallow lacustrine basins developed there dried.

According to the petrostructural and AMS (anisotropy of magnetic sensibility) data (*Ivanov* et al., 2001), the combination of felsic (rhyodacite to dacite) and mafic (andesite to basaltic andesite) sequences in southern part of the Panagyurishte ore region are the result of mingling and mixing of basic and granitic magmas, generated at crust or crust-mantle levels. The plutonic bodies represent the hypo-abyssal and abyssal parts of an island arc magmatic system (*Ivanov* et al., 2001; *Von Quadt* et al., 2001) that could be attributed to a small degree of crustal melting induced by the injection of mafic asthenospheric magmas as a possible result of the subducting slab detachment (*Neubauer, 2002*).

Ore deposits geology

The Elshitsa ore deposit is situated close to the southern margin of the Elshitsa pluton (Figs. 1, 2). The Elshitsa fault has a trend of 110 to130^{0}, dips steeply to the NE at 75 to 85^{0} (Figs. 1, 2A), and is the main ore-controlling structure where it intersects the N-NW strike-slip faults (*Bogdanov,* 1987). Quartz-sericite (illite±smectite) and propylitic (albite-chlorite-epidote ± calcite) styles of alterations are the most common (Table 1) in the andesites and dacites at Elshitsa. Adularia alterations are rarely observed, while the advanced argillic and quartz-diaspore alteration have been observed in the footwall of the massive pyrite ores (*Radonova* and *Velinov*, 1974; *Strashimirov* and *Popov,*

2000). Two compositionally distinct types of ore can be recognized (Fig. 3, Table 1): ores dominated by massive pyrite, and pyrite-chalcopyrite with minor galena, sphalerite and gold. The early massive pyrite ore bodies were formed in the eastern part, followed by later Cu-Au sulphide ore bodies in the central and western parts of the deposit (Fig. 3). Rare galena-sphalerite veinlets also occur, cutting the pyrite-chalcopyrite ore bodies. Lenticular and lens-like ore bodies are characteristic of the upper parts, while the sheet-like disseminated, vein and stringer ore bodies are commonly observed in the deeper parts of the deposit (Fig. 3). The thickness of the ore bodies varies from several meters up to 50 m; the length from several meters up to 250-300 m horizontally and up to 500 m vertically. The sulphide mineralization in the inner parts of ore bodies is predominantly massive and changes gradationally from veinlet to disseminated on the periphery.

The Radka ore deposit is located within the northern part of the Elshitsa volcano-intrusive structure, 3 km S-SE of the village of Popintsi (Fig. 1B). The andesite and dacite lava flows, agglomerate and lapilli tuffs have an W-NW strike and dip 25-45° N-NE (Fig. 1B). The effusive rocks are intersected by several sub-volcanic dacite dykes with varying thickness (Fig. 4). The sub-vertical dyke-like granodiorite porphyry intrusion was found at depth by drilling and mining works (Fig. 4). The E-NE, NW and NE faults played a considerable role in increasing of the permeability of the host andesite volcanic rocks. The ore bodies are distributed in a complicated V-shaped block, bordered by a group of conjugate faults (Fig. 4).

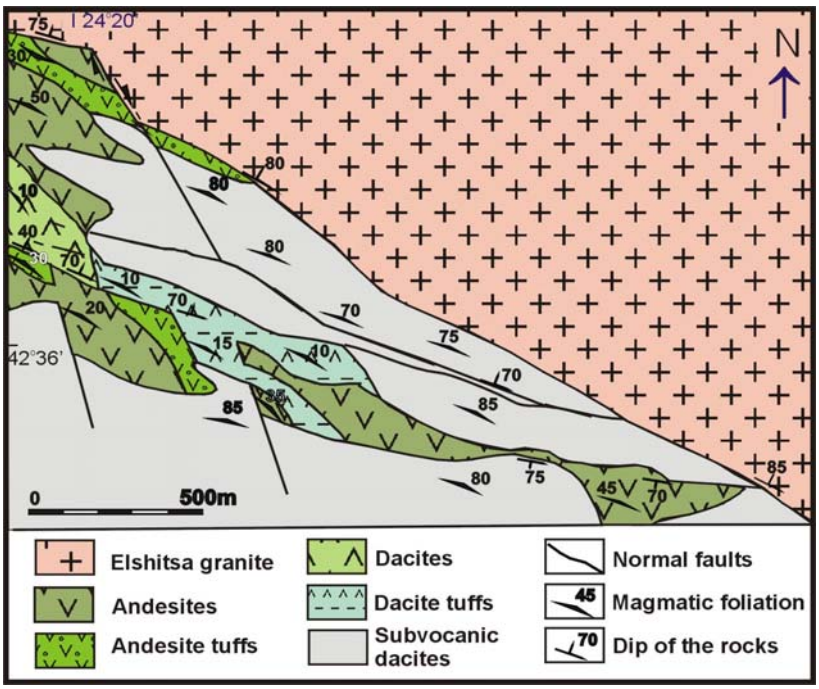

Figure. 2. Geological map of Elshitsa deposit (modified after Bogdanov et al., 1972).

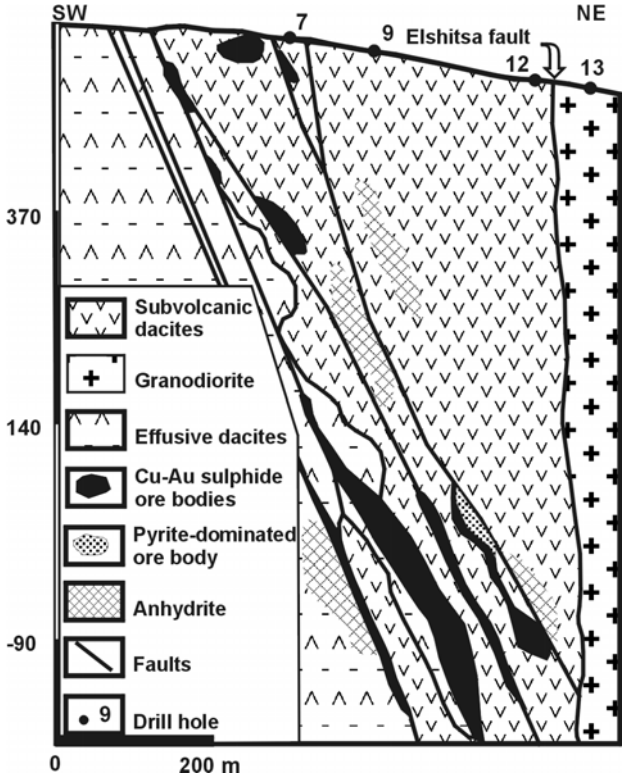

Figure 3. Cross-section of Elshitsa deposit (modified after Bogdanov and Popov, 2003).

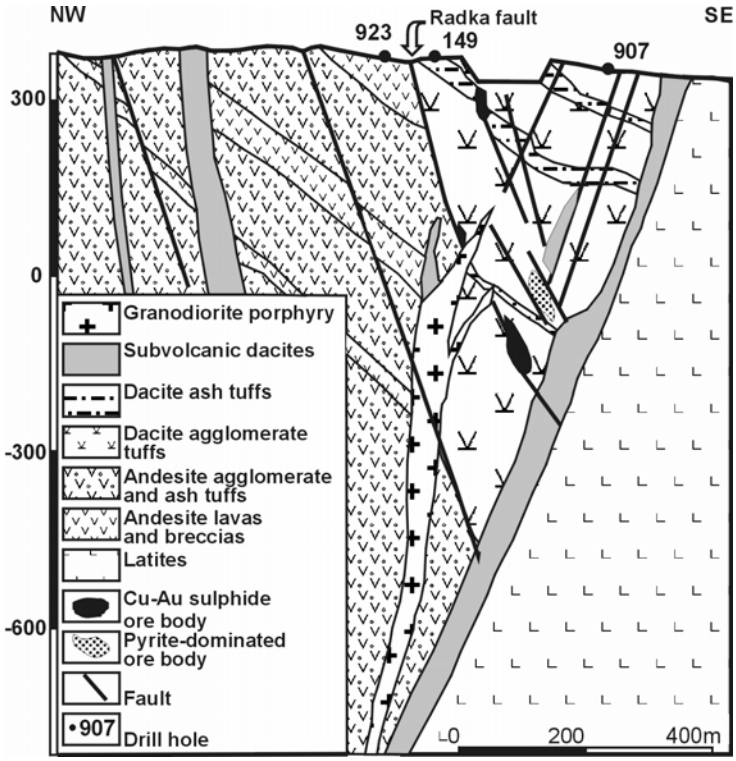

Figure 4. Cross-section of Radka ore deposit (After Tsonev et al., 2000; Bogdanov and Popov, 2003).

Quartz-sericite (illite±smectite) and advanced argillic alteration affect the inner parts of the effusive rocks close to the ore bodies, while in the outer parts the propylitic alteration predominates (*Radonova* and *Velinov*, 1974). The pyrite and Cu-Au sulphide (copper-pyrite) ore bodies occur as columnar, lens-like, or pipe-like shapes (Table 1, Fig. 5). Mainly the fault zone with a W-NW

direction and dip to the north controls their position. Ore shoots of massive pyrite-chalcopyrite and bornite ores with isometric or irregular shapes, diameters from 2 to 30 m and 10-50 m long in depth are characteristic for Radka. Low-grade typically veinlet-disseminated ores also occurred and were mined by open pit close to the surface. The ore bodies crosscut the bedding of the andesite and dacite tuffs and are rarely sub-parallel. According to the mineral composition, massive pyrite-dominant and Cu-Au-sulphide (pyrite-chalcopyrite, bornite-chalcopyrite-chalcocite-tennantite and galena-sphalerite-chalcopyrite) ore bodies can be recognized (Fig. 5).

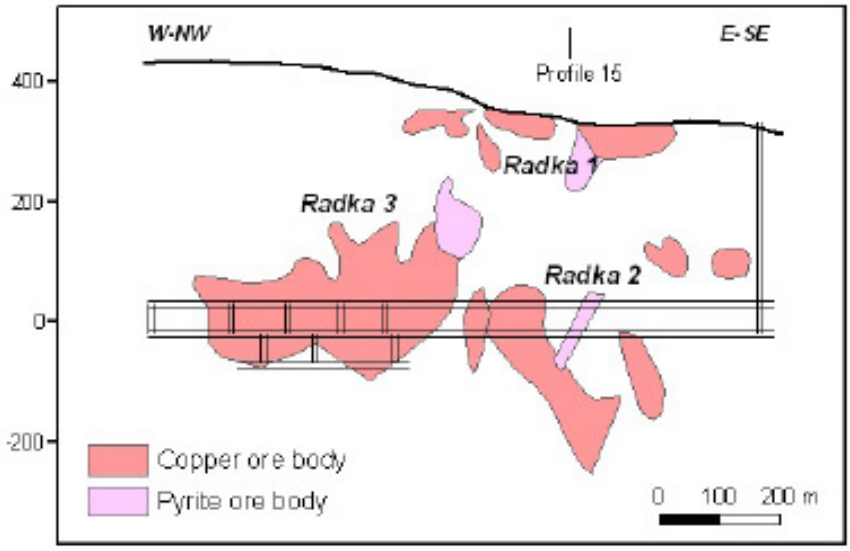

Figure 5. Longitudinal projection of Radka ore deposit (After Bogdanov and Popov, 2003).

The Krassen ore deposit is located within an 80 to 100 m thick fault zone, limited by two sub-parallel fault arms trending 110 to 115° and dipping 50 to 65° to NE (Figs. 6, 7). The pyrite-enargite dominated mineralization is tectonically controlled by a series of sub-parallel zones of tectonic breccias that host the pyrite-enargite ore bodies (Fig. 7). The northern splay of the Krassen fault zone is marked by development of tectonic clay and brecciated sulphide that is evidence for post-mineral fault reactivation.

The Krassen deposit represents a pipe-like tectonic breccia zone affected by intense quartz-sericite (illite±smectite) and advanced argillic quartz-kaolinite (dickite) alteration (*Strashimirov* and *Popov,* 2000), in which individual lens-like and columnar ore bodies are located (Fig. 7). This zone has an ellipse-like section, 300 to 100 m in length, a dip of about 50° to NE and can be traced intermittently to a depth of 700 m. Most of the ore bodies are lenticular in shape (Fig. 7). Pyrite, chalcopyrite, covellite and bornite are widespread, but the enargite is most abundant ore mineral in the Krassen deposit (Fig. 3D), placing the deposit firmly within the high sulphidation style of mineralisation (*Sillitoe*, 1983; *Hedenquist et* al. 1996, 2000). Enargite-chalcopyrite-bornite mineralization is dominant in the western part of the deposit. A series of massive pyrite-enargite lenses (Fig.7), containing subordinate chalcopyrite and bornite, are characteristic of the central part of the deposit. Low-grade vein pyrite is common in the eastern part of Krassen.

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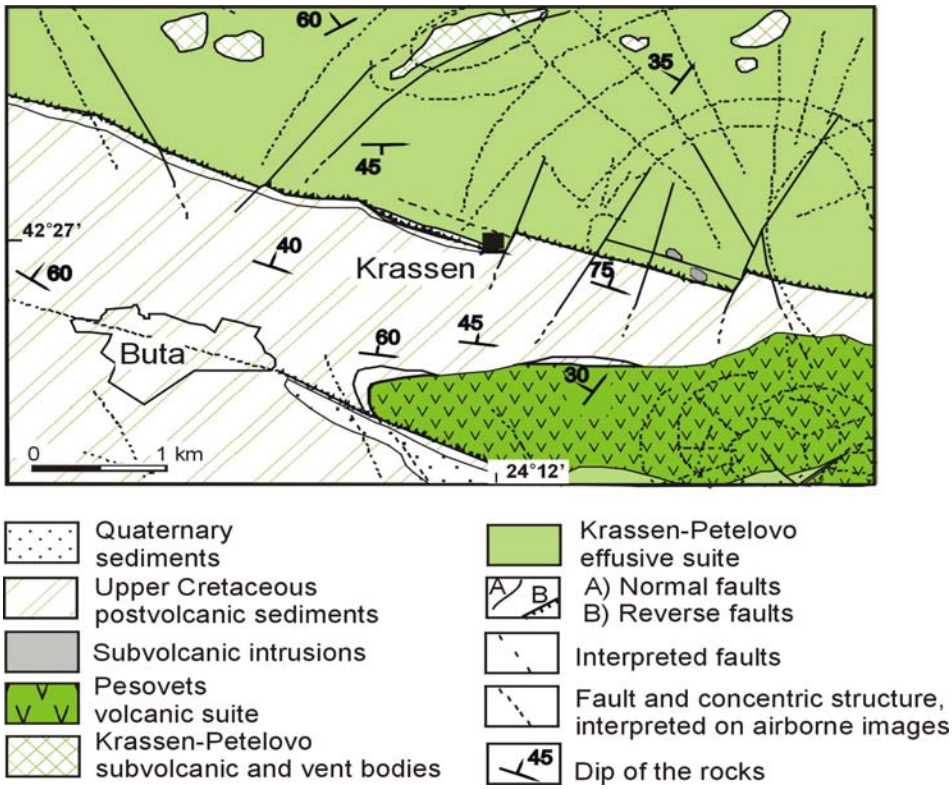

Figure 6. Geological map of the Krassen deposit (after Popov and Popov, 2000).

Ore mineralogy

For the last 70 years the gold-bearing mineral assemblages and mineralization processes of these epithermal deposits have been studied by many researchers (Dimitrov, 1960; Tsonev, 1974; Bogdanov, 1980, 1987; Bogdanov et al., 1997, 2005; Strashimirov and Popov, 2000; Kouzmanov, 2001, Bogdanov and Popov, 2003 and many others).

The mineral assemblages of the ores at the Elshitsa, Radka and Krassen are similar and differ only by the amount of tennantite, bornite, enargite and trace minerals of Ga, Ge, In, Bi, Sn, Se and Te that are present. The ore mineralogy is dominated by pyrite and chalcopyrite (Elshitsa), pyrite, chalcopyrite and bornite (Radka) and pyrite and enargite (Krassen), which form more

than 90% of the sulphide volume of the main ore bodies. The parageneses in the Elshitsa, Radka and Krassen deposits could be related to eight mineral assemblages: **Early** (1) Pyrite-quartz assemblage; **Main** (2) Chalcopyrite-pyrite; (3) Enargite-pyrite; (4) Bornite-tennantite and; (5) Galena-sphalerite-chalcopyrite; **Late** (6) Quartz-pyrite (7) Pyrite-marcasite and (8) Anhydrite-gypsum assemblages (Table 2, Fig. 7).

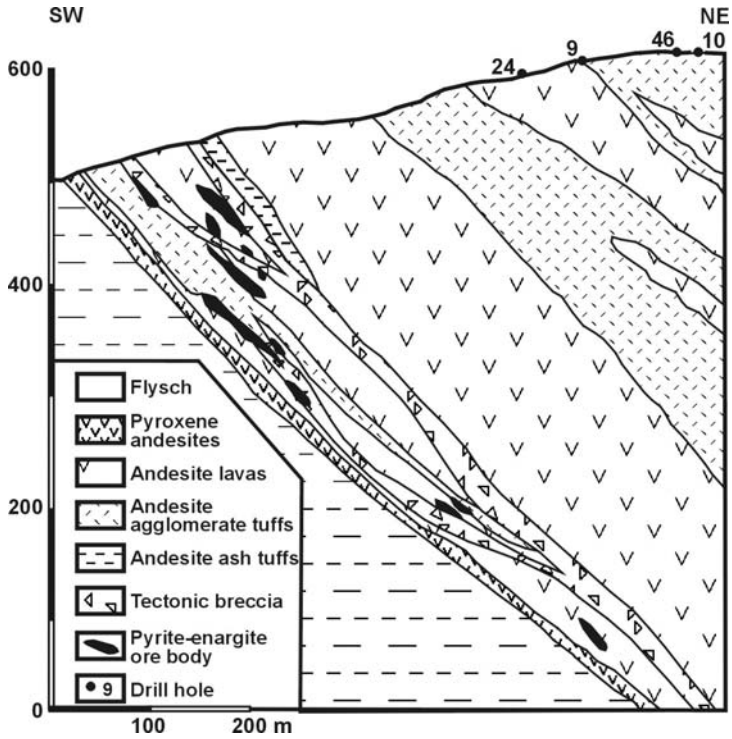

Figure 7. Cross-section of Krassen Cu-Au epithermal deposit(Modified after Bogdanov and Popov, 2003).

In **Elshitsa deposit** the *early mineral assemblage* is dominated mainly by pyrite with atoll-like, colloform and zonal textures (Fig. 8B) associated with quartz and rare 1-20µm relicts of rutile, cassiterite and titano-magnetite. The colloform pyrite contains 1 - 3 ppm Au and 0.24—1.67 wt% As (Todorov, 1991; Bogdanov et al., 1997). Clastic deformation of pyrite is widespread with quartz, chalcopyrite (Fig. 8C), galena and sphalerite breccia fillings.

Table 2. Mineral assemblages in Elshitsa, Radka and Krassen deposits

STAGES	ALTERATIONS		EARLY	MAIN				LATE		
Mineral assemblages Minerals	Adularia-sericite	Kaolinite-alunite	Pyrite-quartz	Chalcopyrite pyrite	Enargite-pyrite	Bornite - tennantite	Galena-sphalerite-chalcopyrite	Quartz-pyrite	Pyrite-marcasite	Anhydrite-gypsum
Quartz	▬■■■■	▬■■■■	▬■■	▬■■■	▬▬	▬▬	▬▬	■■■■	▬▬	-
Sericite	▬▬▬									
Chlorite	▬▬▬									
Adularia	▬▬▬▬									
Alunite		▬▬								
Kaolinite		■■■■								
Pyrophyllite		▬								
Dickite		▬								
Cassiterite			-							
Ti-magnetite			--							
Rutile			-							
Pyrite			■■■■	■■■■■	■■■■	▬■■	▬■■	■■■■	▬■■	----
Gold			▬	▬▬	▬▬	▬■■	▬▬■			
Electrum				▬	▬▬	▬▬	▬■■	-	-	--
Chalcopyrite				■■■■■	■■▬	▬■	■■■			---

Wittichenite				-						
Emplectite				-						
Friedrichite				-						
Hammarite				-						
Aikinite				-						
Tetradymite				-						
Tsumoite				-						
Bismuth				-						
Micharaite				-						
Tennantite					▬	■■■■■■	--			
Enargite					■■■					
Luzonite					▬					
Bornite						■■■■■■■				
Idaite						-				
Renierite						-				
Germanite						-				
Vinciennite						-				
Stannite						-				
Briartite						-				
Kesterite						-				
Colusite						-				
Digenite						-				
Goldfieldite						----				
Chalcocite						-▬■■■				
Tellurium						-				
Altaite						-				
Sulvanite						-				
As-sulvanite						-				
Tetrahedrite						-	▬			
Gallite							-			
Roquesite							--			
Sphalerite						----	▬■■▬			--
Galena						----	▬■■▬			--
Silver						---	-▬-			---
Betekhtinite							-			
Hessite							-			
Covellite							■■▬			
Marcasite									■■▬	
Calcite										▬
Barite										■▬
Anhydrite										■■■■■■
Gypsum										■■■■■■
Mordenite										--
Heulandite										--
Laumontite										--
Stilbite										--
Elshitsa	⊕⊕⊕⊕	⊕	⊕⊕⊕⊕	⊕⊕⊕	⊕	⊕⊕	⊕⊕	⊕⊕⊕	⊕	⊕⊕⊕⊕
Radka	⊕⊕⊕	⊕	⊕⊕⊕	⊕⊕	⊕⊕	⊕⊕⊕⊕	⊕⊕	⊕⊕⊕	⊕	⊕⊕⊕⊕
Krassen	⊕⊕	⊕⊕⊕	⊕	⊕	⊕⊕⊕⊕	⊕	⊕	⊕⊕	⊕	⊕⊕⊕

⊕ - very rare ⊕⊕ - rare ⊕⊕⊕ - common ⊕⊕⊕⊕ - abundant

Except for pyrite, chalcopyrite is the dominant sulphide in the *main mineral assemblages* (Table 2) and occurs as massive lenses and veinlets. Tennantite-tetrahedrite mineral series, galena and sphalerite are subordinate. NAA data (Todorov, 1991) indicate Au content at the range of 3.77-14.70 ppm in pyrite and 0.24-1.24 ppm in chalcopyrite. Enargite occurs as rare 5-50μm irregular shaped grains associated with pyrite, tennantite and sphalerite only in the upper horizons of Elshitsa suggesting only a local importance of the early HS fluids.

The galena-sphalerite-chalcopyrite mineral assemblage is characterized by the deposition of galena, sphalerite, pyrite, bornite, covellite and chalcopyrite, as well as tennantite-tetrahedrite series minerals. All these minerals are carriers of Au and Ag. Both tennantite and galena contains Te minerals observed as rare sub-5μm inclusions identified as stoichiometric altaite $Pb_{1.0}Te_{1.0}Se_{0.02}$ and hessite $Ag_{2.0}Te_{1.0}$. The bismuth minerals in Elshitsa are represented by Se-

bearing aikinite with composition $(Cu_{0.95}\ Fe_{0,01})_{0.96}Pb_{1.12}\ Bi_{0,90}(S_{2,91}\ Se_{0,10})_{3.01}$, native Bi and tetradymite, which are associated with the opaque minerals of the chalcopyrite-pyrite assemblage. There is a clear record of crosscutting and replacement relationships between the early pyrite-dominated ores and later copper-rich mineralization (Fig. 7C). Both are crosscut by the latest quartz-pyrite (Fig. 7F) and anhydrite veins.

The *late mineral asssemblages* (Table 2) consists of quartz-pyrite and anhydrite-gypsum veins cross-cutting and replacing minerals assemblages from earlier stages. The widespread late quartz-pyrite assemblage is found as W-NW trending veins of milky quartz ranging from mere stringers up to 1-5 cm wide (Fig. 8F) and up to 50 m long, with {100} and {210} pyrite with up to 2-3 cm edge length. The late anhydrite-gypsum mineral assemblage is represented by anhydrite, gypsum and barite veins and lenses replacing the sulphide ore. Marcasite in assemblage with pyrite implies that the hydrothermal conditions were quite acid and lower temperature in the late mineral assemblages.

Native gold has been found in all eight mineral assemblages, but it is most abundant in galena-sphalerite-chalcopyrite assemblage, where it occurs as microscopic flattened, elongate, or irregular single grains that rare exceed 0.2 mm in size (Bogdanov et al., 1997).

The *early pyrite assemblage* in **Radka deposit** is represented mainly by colloform-textured pyrite, containing 0.80 - 4.17 ppm Au as indicated by NAA data (Todorov, 1991), due to dispersed particles of sub-microscopic gold. Chalcopyrite, bornite, covellite and tennantite-tetrahedrite are dominant minerals in the *main assemblages* (Table 2) and occur as intergrown massive aggregates, commonly containing 10-80μm blebs of goldfieldite that seems to be the main Te carrier. As an important gold carrier bornite typically contains 8.10 - 41.80 ppm Au as indicated by NAA data of Todorov (1991). Enargite is rare and occurs only in upper levels at Radka. Exotic rare Ga, Ge, In and Sn minerals occur as 1-10μm inclusions within bornite, tennantite, galena and sphalerite, and as a rule accompany elevated Au concentrations in the HS-epithermal ores. Microanalytical data confirmed the following trace minerals: roquesite $(Cu_{1.11}Zn_{0.05}Fe_{0.01})_{1.17}In_{1.0}S_{2.08}$, gallite $Cu_{0.99}(Ga_{0.85}Fe_{0,09}Zn_{0.08})_{1.02}S_{2.00}$, germanite $(Cu_{22.32}Zn_{2.72}\ Fe_{1,52})_{26.56}(Ge_{4.64}As_{0.52})_{5.16}S_{31.64}$, briartite $Cu_{1.98}(Zn_{0.68}Fe_{0.38})_{1.06}(Ge_{1.01}As_{0.01})_{1.02}S_{3.96}$, renierite $Cu_{9.94}(Fe_{3.67}Zn_{0.40})_{4.07}(Ge_{1.87}\ As_{0,13})_{2.00}S_{15.99}$. Micron-sized inclusions of Sn minerals such as vinciennite $Cu_{10.16}Fe_{3.90}\ Sn_{1.00}As_{0.94}S_{15.98}$, stannite $Cu_{2.02}Fe_{1.05}Sn_{1.0}S_{4.11}$, kesterite $Cu_{2.05}(Zn_{0.74}\ Fe_{0.19})_{0.93}\ Sn_{0.93}\ S_{4.06}$, kiddcreekite $Cu_{6.01}Sn_{1.00}\ W_{1.00}\ S_{7.98}$, and buckhornite $Au_{0,77}\ Pb_{1,92}\ (Bi_{0,60}\ Fe_{0,47})_{1,07}\ Te_{1,92}\ S_{3,33}$ that have been identified in the bornite-tennantite and the galena–sphalerite-chalcopyrite assemblages, suggest a close link between epithermal and porphyry environment.

Bismuth minerals in Radka are represented by 5-10μm lamellar inclusions of aikinite-bismuthinite series in addition to wittichenite (Bogdanov et al., 1997; Kouzmanov, 2001;Bogdanov and Popov,2003) and the rare Bi-telluride, tsumoite $Bi_{1.0}Cu_{0.03}Te_{1.06}$, found in

association with the minerals of the chalcopyrite-pyrite assemblage. Bi minerals are locally abundant and associated with gold and chalcopyrite, often indicating Au-enrichment.

The *late assemblages* (Table 2) consist of quartz-pyrite and anhydrite gypsum veins, which crosscut and replace minerals from the earlier mineralization stages. The anhydrite veins and lenses are abundant in the deeper horizons of Radka deposit while gypsum is more common at upper levels. Native gold (Fig. 8E) is more abundant in the enargite-pyrite, bornite-tennantite and galena-sphalerite-chalcopyrite assemblages. The gold is 0.1-100 μm in size and commonly associated withbornite, tennantite, chalcopyrite, sphalerite and galena. Macroscopic (>100 μm) gold and electrum grains and aggregates of gold up to 5 mm are rarely found in the bornite-tennantite-chalcocite oresin Radka deposit (Fig. 8G). Electrum and gold occur as blebs or irregular particles in the sulphide minerals, or along grain boundaries. The elongate, isometric and ellipse-like gold grains are most commonly found in assemblages with enargite, bornite, tennantite, chalcopyrite, galena and chalcocite. Anhedral and sharp-edged gold grains, or short veinlets are also present in some cases. Native silver was found in wiry forms (Fig. 8H), as thin native silver veinlets, not exceeding 0.5 mm in width and up to 5 cm in length and as irregular inclusions in bornite. In Radka, the silver is Hg bearing. The gold grade in the primary ore is 1-3 g/t, rarely up to 8-10 g/t, and has been extracted as a by-product from both the pyrite and copper concentrates.

The ore mineralization in **Krassen deposit** is comparable to Radka, but enargite is much more abundant and characteristic (Fig. 8D) for individual orebodies at Krassen. The *early assemblage* is represented mainly by colloform-textured pyrite with up to 16.10 ppm Au (Todorov, 1991), which occurs as anhedral disseminations and aggregates(Fig. 8A) Enargite $Cu_{3.14}(As_{1.0}Sb_{0.02})_{1.02}(S_{3.71}Se_{0.01})_{3.72}$ is very abundant and is observed replacing the early pyrite, or in association with chalcopyrite, bornite and chalcocite in the *main mineral assemblages* (Table 2). The enargite-rich ore bodiesare also gold rich with grades up to 6-8 g/t. Aikinite with close to the stoichiometric composition $Cu_{1.0}(Pb_{1.04}Ag_{0.01})_{1.05}(Bi_{1.04}As_{0.03})_{1.07}S_{3.08}$ was identified as sub 10μm lamellar inclusions in chalcopyrite and seems to be the most common Bi phase in the all three deposits. *Late quartz-pyrite vein assemblage* in Krassen is not as abundant as compared to the Radka and Elshitsa deposits.

Gold in the early massive pyrite in Elshitsa, Radka and Krassen is sub-microscopic in size (< 0.1 μm) i.e., so-called “invisible” gold (Bogdanov et al., 1997). The deformation and recrystallization of the ore bodies and overprinting of the early sulphide assemblages by later stages caused Au and Ag migration to cracks and grain boundaries of the sulphide minerals. As a result of these processes, the native gold and electrum grain size increases from sub-microscopic (< 0.1 μm) in the early colloform pyrite to microscopic (0.1-100 μm) and macroscopic (>100 μm) in the late gold-sulphide assemblages (Bogdanov et al., 1997). The electrum fineness in

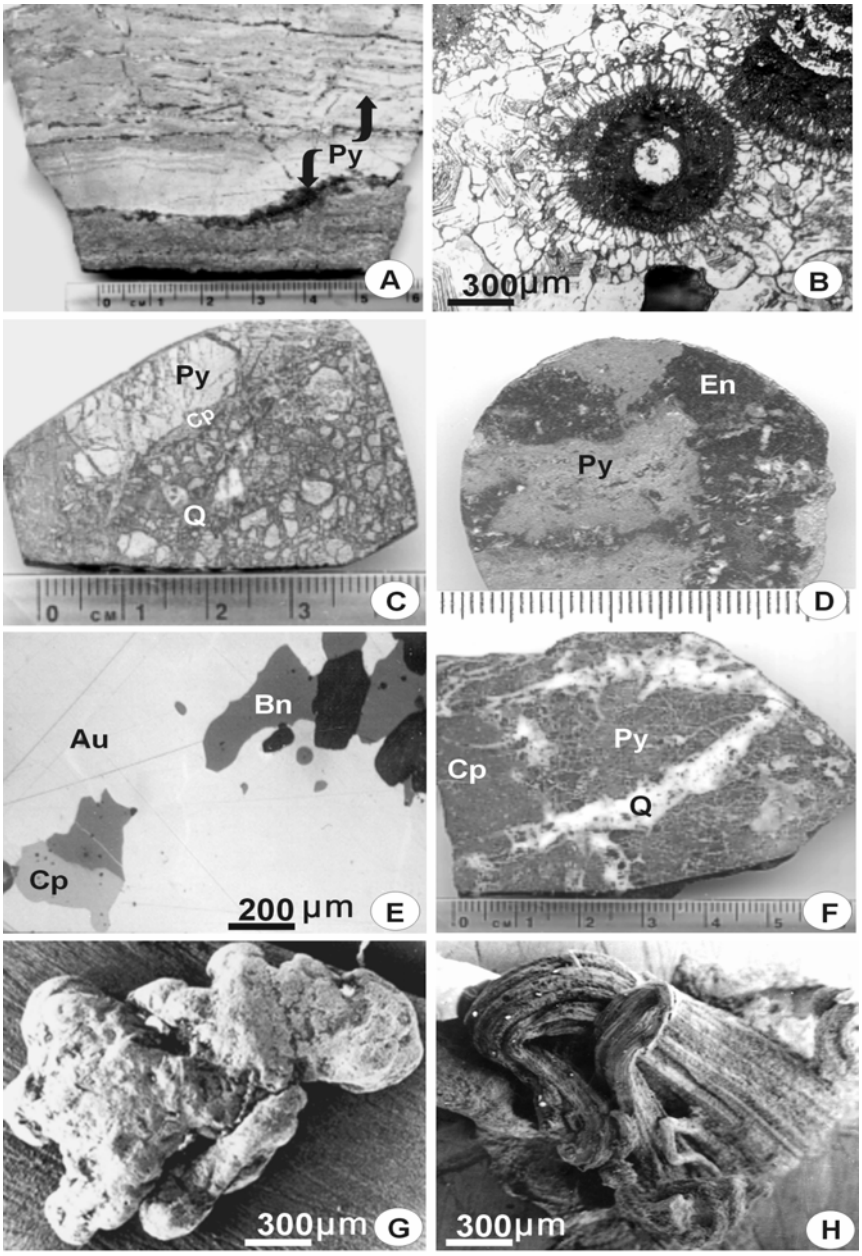

Figure 8. Early and main mineral assemblages: A- dacite tuff from Krassen with pyrite (Py) lamination (scale in cm); B- zonal texture of colloform pyrite (Early pyrite-quartz assemblage) from Elshitsa deposit; C -pyrite (Py) breccia replaced and crosscutted by chalcopyrite (Cp) and quartz (Q) from the chalcopyrite-pyrite assemblage; D- Early pyrite (Py) replaced by enargite (En) from Krassen deposit (scale in cm); E- gold (Au) in assemblage with bornite (Bn) and chalcopyrite (Cp), Radka deposit; F- early pyrite (Py) and (Cp) chalcopyrite chalcopyrite-pyrite assemblage) crosscutted and replaced by the late vein quartz (Q), (scale in cm); G -gold extracted from bornite-chalcopyrite ore, Radka deposit, SEM; H - native silver from Radka

individual grains varies between 764 and 998, as estimated by 126 microprobe analyses, characteristic for the epithermal class of mineral deposits (Morrison et al., 1991). Cu, Te, Sb and Bi are the most common trace elements in gold and electrum in Elshitsa, Radka and Krassen. Massive pyrite and pyrite- veinlet and disseminated ore bodies are poor in gold and other precious metals, as compared to the ore bodies with more complex mineral compositions. The

latter are rich in enargite, chalcopyrite, chalcocite and bornite, and are also important Ga, Ge, Se and Te carriers.

Ore genesis

The Cu-Au sulphide ores are considered to be of hydrothermal and replacement origin (Dimitrov, 1960; Tsonev, 1984; Bogdanov, 1984, 1987; Bogdanov et al., 1997, 2005; Kouzmanov, 2001; Bogdanov and Popov, 2003). They formed later than the pyrite bodies following intrusion of the sub-volcanic rhyodacites, replacing the volcanic dacites, andesites and associated pyroclastites and rhyodacite dykes. The late quartz-pyrite vein (Fig. 4F) and anhydrite-gypsum mineral assemblages are characteristic for the Elshitsa, Radka and Krassen as well as for the closely associated porphyry copper deposits (Fig. 1) suggesting a common source and close link between the individual porphyry and epithermal systems.
Based on existing data, the formation of the Cu-Au epithermal deposits could be integrated into a single broad event of contemporaneous formation of epithermal and porphyry systems related to and surrounding magmatic centres, including: 1. Formation of early massive pyrite ores towards the end of the dacite volcanism. 2. Contemporaneous formation of the epithermal Cu-Au mineralization in the upper parts of the epithermal-porphyry systems. 3. Formation of the late quartz-pyrite and anhydrite veins characteristic of both epithermal (Elshitsa, Radka and Krassen) and porphyry-copper (Vlaikov Vruh, Tsar Assen, Petelovo) deposits (Fig. 1).

According to fluid inclusion studies (Bogdanov, 1987; Strashimirov et al., 2002; Kouzmanov , 2001; Tarkian et al., 2003) there is evidence for high salinity (28-64% NaCl eq) and low salinity (2-6% NaCl eq) fluids being present over the life of the hydrothermal systems. Hot (325-379 ^{o}C) and saline fluid (up to 64% NaCl eq) is characteristic of the porphyry environment in the Panagyurishte district. In contrast, liquid-rich, medium to high temperature (260-310°C) and more dilute (4.7-5.9% NaCl eq) fluid that is typical of the Radka, Krassen and Elshitsa epithermal systems, transported considerable amounts of Cu, As, Fe and Au. The successive hydrothermal phases of the discrete evolving volcano-plutonic systems precipitated chalcopyrite and the high sulphidation ore assemblage consisting of enargite, chalcocite and gold minerals in the Krassen deposit. Rare remnants of enargite, indicative of localized high-sulphidation conditions are preserved in the Elshitsa intermediate-sulphidation epithermal system, whereas Radka represents a transitional epithermal system with an intermediate to local high sulphidation style of oremineralization. Enargite in the leached residual quartz zones is more abundant here compared to Elshitsa. Anhydrite veins formed as temperature waned in the late stages of three systems.

Recrystallization of the sulphide minerals suggest tectonic and hydrothermal ore remobilisation during the evolution of epithermal and porphyry systems in accordance with the similar $\delta^{34}S$ values for the main sulphide minerals (Fig. 9) in Radka ($\delta^{34}S$ =-6.7 to -1.8) and Elshitsa ($\delta^{34}S$ =-5.6 to +0.5) epithermal deposits and for Vlaikov Vruh ($\delta^{34}S$ =-5.3 to +4.0) porphyry copper deposit, indicating a magmatic source for sulphur. Comparison of the Pb isotope values of the main sulphide minerals ($^{206}Pb/^{204}Pb$=18.49-18.76; $^{207}Pb/^{204}Pb$=15.61-15.64; $^{208}Pb/^{204}Pb$=38.53-38.80) from Elshitsa, Radka and Vlaikov Vruh deposits with those of the

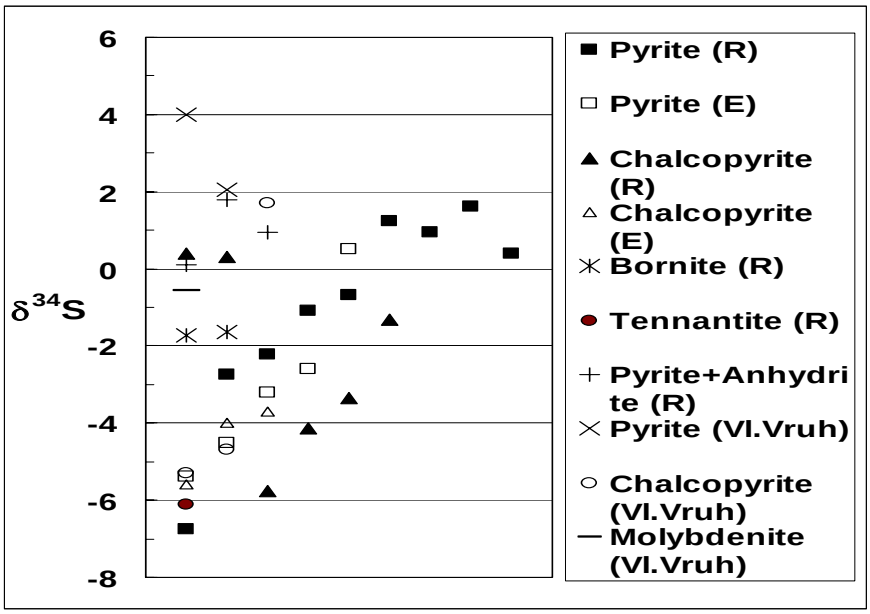

Figure 9. Sulphur isotope ratios in Radka (R) and Elshitsa (E) epithermal deposits and Vlaikov Vruh porphyry-copper deposit (data by Angelkov, 1974; Velinov et al. 1978; Kouzmanov, 2001).

Elshitsa granite ($^{206}Pb/^{204}Pb$=18.56-18.57; $^{207}Pb/^{204}Pb$=15.63-15.65; $^{208}Pb/^{204}Pb$=38.60-38.66) and the porphyry granodiorite of Vlaikov Vruh ($^{206}Pb/^{204}Pb$=18.61-18.77; $^{207}Pb/^{204}Pb$=15.62-15.66; $^{208}Pb/^{204}Pb$=38.61-38.82) suggest that the latter two were sources of the metals (Amov et al., 1974; Kouzmanov 2001). The $^{87}Sr/^{86}Sr$ ratios of anhydrite, gypsum, barite and calcite from Radka and Elshitsa epithermal deposits and Vlaikov Vruh porphyry copper deposit reported by Kouzmanov (2001) are between 0.7058 and 0.7072, suggesting some mixing of strontium from the dacitic host rocks ($^{87}Sr/^{86}Sr$=0.7058-0.7061) and ^{87}Sr enriched basement rocks ($^{87}Sr/^{86}Sr$=0.7085-0.7154).

Andesite-dominated magmatic activity in the Panagyurishte structural corridor (Fig. 1) has a life span from Turonian to Maastrichtian that is about 25 Ma, while the formation of the porphyry-epithermal systems of Elshitsa-Vlaikov Vruh, Radka-Tsar Assen, and Krassen-Petelovo (Fig. 1) appears limited to a narrower time interval of 1-5 m.y. (Lilov and Chipchakova,

1999; Peytcheva et al., 2001, 2003). The recent Re-Os dating of molybdenite (82,1±0,6 Ma) from Vlaikov Vruh (Kouzmanov, 2001) and U-Pb zircon data (81.2 +0.5/-0.7 Ma and 82.3 ±0.5Ma) for the Elshitsa granite (Peytcheva et al., 2003) indicate a possible narrow interval of formation for the linked epithermal and porphyry deposits.

Main features of the Cu-Au epithermal deposits

Epithermal deposits of intermediate (Elshitsa) and intermediate to local high (Radka, Krassen) sulphidation style of ores and porphyry copper deposits evolved in close proximity within three individual volcano-plutonic centers (Elshitsa-Vlaikov Vruh, Radka-Tsar Assen, and Krassen-Petelovo). The close connection between the andesite-granodiorite volcano-plutonic structures facilitates the multistage and polycyclic character of their hydrothermal systems. The similar character of the epithermal ores and the mineral assemblages in Elshitsa, Radka and Krassen deposits and their discrete trace mineralogy reflects the varying fS_2/fO_2 states in the individual epithermal deposits, depending on their depth of formation, level of erosion and the link to the porphyry environment.

The Bi-Se-Te and Ga-Ge-In signature with pronounced Au enrichment is a characteristic feature for IS and HS ore environment in the southern part of the Panagyurishte ore district suggesting a comparable sources for the epithermal mineralizing fluids(Bogdanov et al., 2004, 2005).

Bi minerals often occur in close association with gold and chalcopyrite, giving the assemblage significance as potential guide to Au-rich environment. The aikinite derivates are most widespread and persistent minerals in the chalcopyrite-pyrite assemblage and also characteristic for the more deeply eroded hydrothermal systems (Elshitsa).

Se and Te enrichment is characteristic and most abundant in the main mineral assemblages and have greatest affinity to shallower transitional IS to HS type of epithermal systems (Radka, Krassen). The Bi dominant trace mineralogy is characteristic for the ABCD belt (Cook et al., 2002) and reflects, in particular in the southern part of the Panagyurishte ore district the, IS to HS type of epithermal environment (Bogdanov et al., 2004, 2005), suggesting shared magma sources and convergence of the processes in the porphyry-epithermal systems.

As a result of the complex multistage and punctuated hydrothermal process the epithermal deposits of Elshitsa, Radka and Krassen contain Au and Ag in various proportions,

but also rare Ge, Ga, In, Bi, Se, Te, Sn, V and W bearing minerals. The ore remobilization processes facilitate formation of a specific, narrow range of Se, Te, Ga, Ge and In minerals in the bornite-tennantite and galena-sphalerite-chalcopyrite assemblages in Radka and Krassen epithermal deposits, and corresponds to the increasing role of the fS_2/fO_2 control during the transition from IS to HS environment.

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Epithermal gold mineralization from Chala deposit, Eastern Rhodopes , Bulgaria

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Chala deposit is situated in the northern part of the Spahievo ore field in the Eastern Rhodopes, Bulgaria. The base-metal and gold mineralization is a result of the Late Paleogene collisional stage of the development of the magmatic-hydrothermal procesess during the subduction of the African under the Eurasian tectonic plate [2]. The Pb-Zn-Cu ore veins, lenses and disseminated ores are hosted by alunite and diaspore quartzites overprinted by quartz-adularia and sericite alteration of the rhyolite-latite volcanicstes and montzonite intrusive rocks[7,10].
The gold-quartz mineralization is characteristic for the latite-hosted quartz-sericite breccia vein zone No 8 of Chala deposit, where the gold grade is about 4 -10 g/t, and over 20 g/t in some samples. The alteration style of the host rocks in respect to the gold mineralization as well as the main part of the sulphide mineralization (galena-sphalerite-chalcopyrite) give as the reason Chala to be attached more closely to the low-sulphidation type of mineralization[5,7,10,11]. The gold mineralization has been studied in respect to the mineral assemblages, morphology, grain size distribution, chemical composition and fluid inclusions.

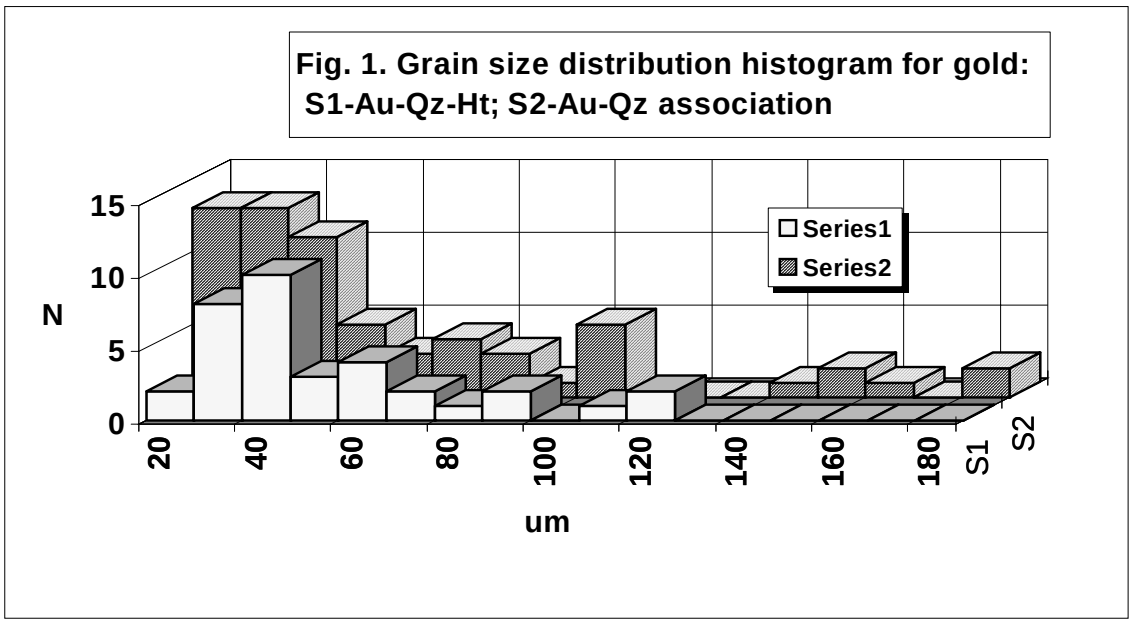
Mineral assemblages

The gold mineralization in Chala deposit is attached to the quartz-gold-adularia assemblage[7], or related to the quartz-specularite-chlorite stage of mineralization[10,11].
The most typical association of the native gold is with grey or milky-white quartz in the silificated latite breccia. The Au grade in the gray quartz is from 9 to 52 g/t, with mean of 20 g/t [9,11]. The recent study has found two types of gold assemblages: 1) Gold-quartz and 2) Gold-quartz-hematite assemblage. Gold in the first assemblage is most commonly observed as compared to the second one. The gold grains in both assemblages are euheral to anhedral with grain size up to 180-120 μm respectively. Fine hematite scales (specularite) are closely associated with the gold grains in the second gold-quartz-specularite assemblage. Often the specularite is oxidized and replaced by secondary Fe oxides such as geothite and limonite. The close spatial association of gold with the host minerals is very important for the gold extraction prosesses[3,4]. Two types of mineral associations can be devided in this respect in Chala deposit as follows: 1) Gold totally enclosed in the host mineral, and 2) Gold at the border of two minerals. The former type is characteristic for the gold-quartz assemblage where the gold grains are enclosed in quartz. In the gold-hematite-quartz assemblage the gold grains were found at the border between quartz and hematite.

Grain size distribution

Anhedral to euhedral gold grains and blebs have been observed in association with quartz metacrystals, hematite (specularite), chlorite and goethite. Inhomogenity and mosaic microtextural patterns have also been commonly observed in the electrum.

The grain size of gold is of primary importance for the assessment of the gold-bearing mineral deposits and for the extracting process and gold recovery[3,4]. Three major classess concerning the gold grain size can be distinguished [3] as follows: **1) Submicroscopic (<0,1 μm); 2) Microscopic (0,1- 100 μm) and 3) Macroscopic (>100 μm**). In 92% of 103 gold grains that have been measured using graduated micrometric scale of *"Amplival Pol U"* microscope and the grain size has been taken as the average of the length and width (fig.1) can be attached to the microscopic class.



More than 50% of the gold grains in both gold-quartz and gold-quartz-hematite associations are from 11 to 40 μm in size. Only 8% of the studied gold grains are macroscopic in size and 2/3 of them are from the gold-quartz association. Submicroscopic grains have not been found that seems to be a result of the process of recrystallization and gold grain coarsening.

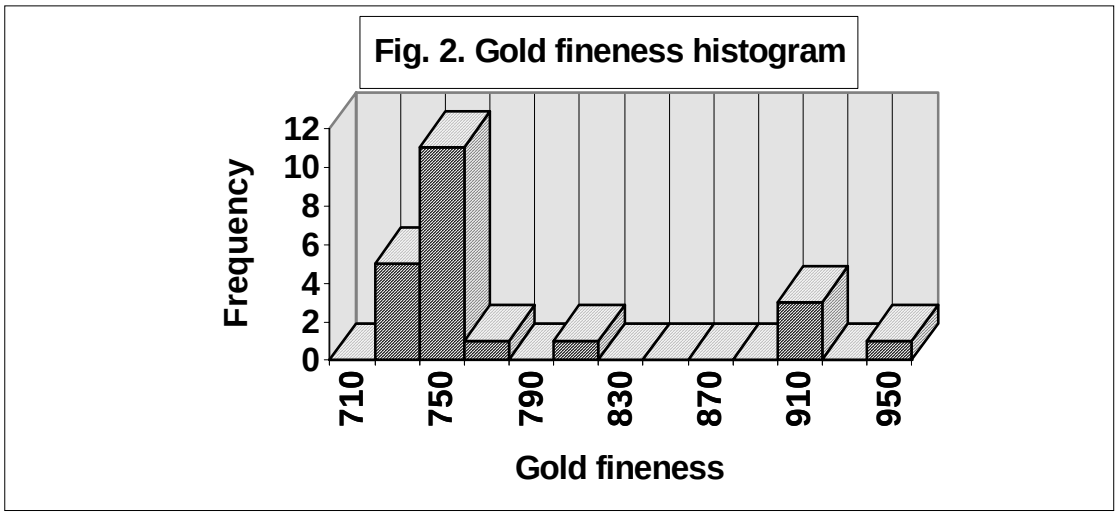
Mineral chemistry

Gold and electrum were discriminated by the 20wt% composition boundary of Ag content in the Au - Ag solid solution as recommended recently[3,4]. Based on 22 microprobe analyses of individual gold grains the gold fineness **[(wt%Au/wt%Au+wt%Ag) x1000]** ranges from 719 to 947‰ with mean of 768‰ (fig. 2, table 1), that is in accordance to the data for epithermal class of mineral deposits (Morrison et al., 1991). As a rule Fe and Cu are most common elements found in the gold grains, while As and Te are less frequent (table 1).

Table 1. Microprobe analyses of gold and electrum from Chala deposit (wt.%)

Au	Ag	Cu	Fe	As	Te	Total
94,45	5,25	0,26	0,38	0	0	100,34
79,45	19,82	0,37	0,17	0	0	99,79
72,49	27,22	0,44	0,58	0	0	100,72
72,00	26,04	0,31	1,44	0	0	99,79
73,03	26,21	0,43	0	0	0	99,67
72,20	26,58	0,36	0,71	0	0	99,85
73,00	26,37	0,32	0	0	0	99,69
70,66	27,08	0,87	0	0	1,0	99,60
71,42	26,84	0,61	0	0	1,09	99,96
70,22	25,68	0,88	1,18	0	1,53	99,49
73,06	23,82	0,49	1,70	0	0,67	99,73
71,04	27,28	0,83	0,40	0	0	99,55
73,15	26,84	0,19	0	0	0	100,17
73,84	27,09	0,19	0	0	0	101,12
73,16	26,28	0,36	0	0	0	99,79
72,51	26,66	0,51	0,12	0	0	99,80
73,59	25,89	0,33	0,14	0	0	99,94
89,73	9,69	0,13	0,08	0,46	0	100,09
88,98	10,71	0,19	0	0	0	99,88
89,08	10,72	0,00	0,19	0	0	99,99
72,36	25,78	0,64	1,23	0	0	100,01
72,15	26,09	0,31	1,45	0	0	99,90

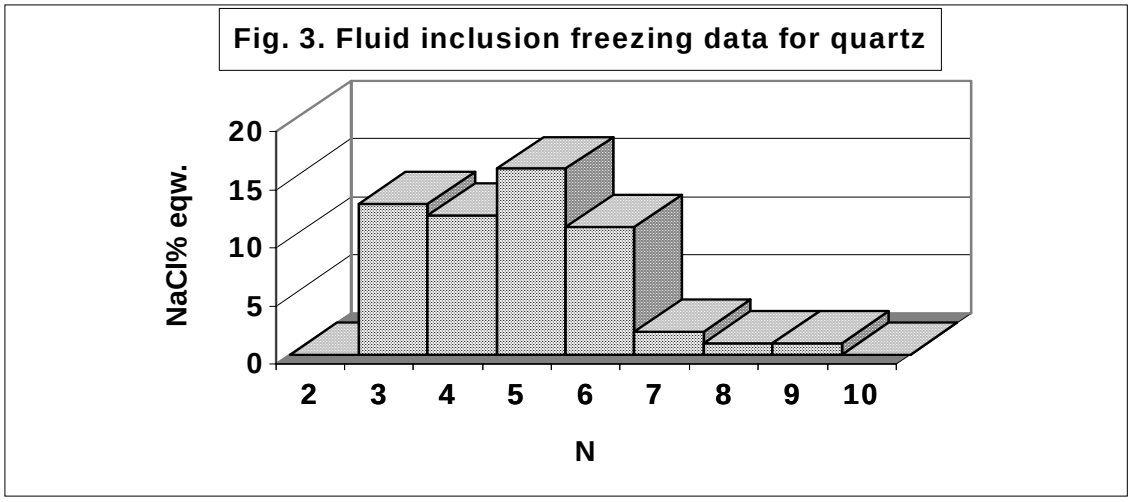
The Ag content in electrum varies between 23,82 and 27,28 wt%. The content variations of other elements in the studied gold grains is as follows (in wt %): Fe - 0,4-1,45; Cu - 0,13-0,87; Te - 0,67-1,53 and 0,46wt% As in one analysis.



Only 9% of the gold is of high finenes over 900‰ that seems to be in proportion tothe grade of recrystallization, as one of the reasons responsible for the Ag migration. The silver is incorporated mainly in isomorphic form in galena from the base-metal mineralization where in some samples exceeds 1000g/t. In the chalcopyrite the Ag content is up to 1700ppm [9,11], while in the tennantite varies from 2900 to 6700ppm[2]. In the base metal ores the Ag grade is about 52g/t[9]. Diffusion of Fe from the host oxides and hydrooxides may be the reason for the highest Fe content in the electrum grains associated with hematite and geothite. The high Te content 1,9 - 1,53wt% in some gold grains is an indicator not only for the "epithermal" nature of gold deposition , but also for the possible presence of gold and silver tellurides such as calaverite ($AuTe_2$), krennerite [$(Au,Ag)Te_2$], petzite (Ag_3AuTe_2) and sylvanite ($AgAuTe_4$).

Fluid inclusions study

According to the previous fluid inclusions studies[8,11] the base-metal mineralization (galena-sphalerite-chalcopyrite assemblage) were deposited within the temperature range of 300-220°C. The recent fluid inclusions data indicate that the gold mineralization were formed at the temperature range 240-180°C. The fluid salinity is not high and ranges from 2,2 to 8,7% NaCl eqw. according to 66 cryometric determinations done on *Chaimeca* freezing stage (fig.3).



Termodynamic data on gold behavior in hydrothermal conditions[6] indicate that in association with hematite the solubility of $AuCl_2$ intensively decrease below pH<4 and log aO_2 values from -20 to -26 at the temperature range 250-200°C that corresponds to the physico-chemical conditions of gold formation in Chala. It seems that the studied epithermal mineralization can be attached more closely to the low sulphidation type of gold than to the high sulphidation one.

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Ada Tepe sedimentary-hosted, low-sulphidation epithermal Au deposit, SE Bulgaria

District: Lat. 41°26' N, Long. 25°39' E

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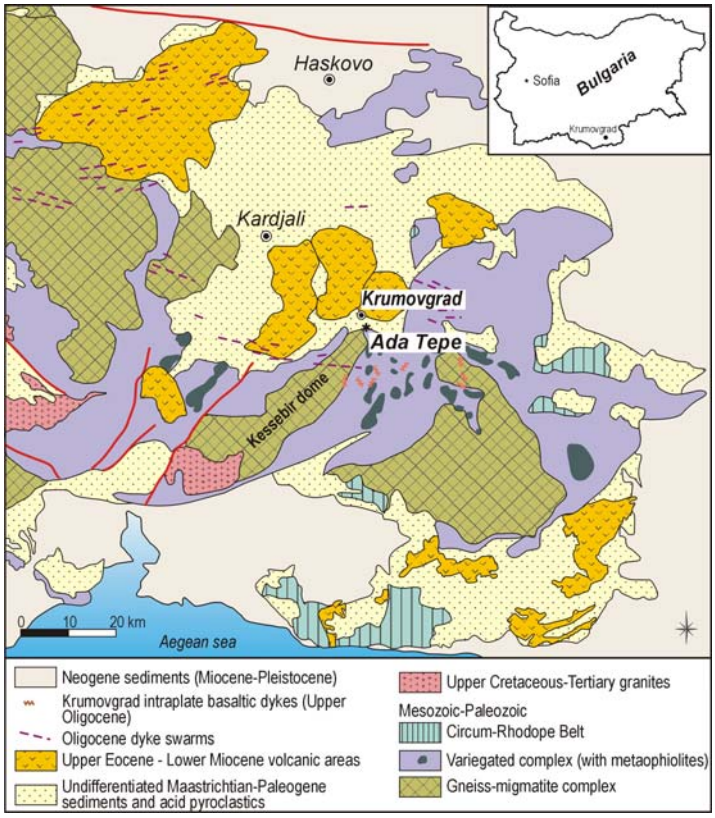
Historical mining and exploration history:
Historical mining activity, probably of Thracian and Roman times. Modern exploration since June 2000 by Balkan Mineral and Mining AD (BMM).

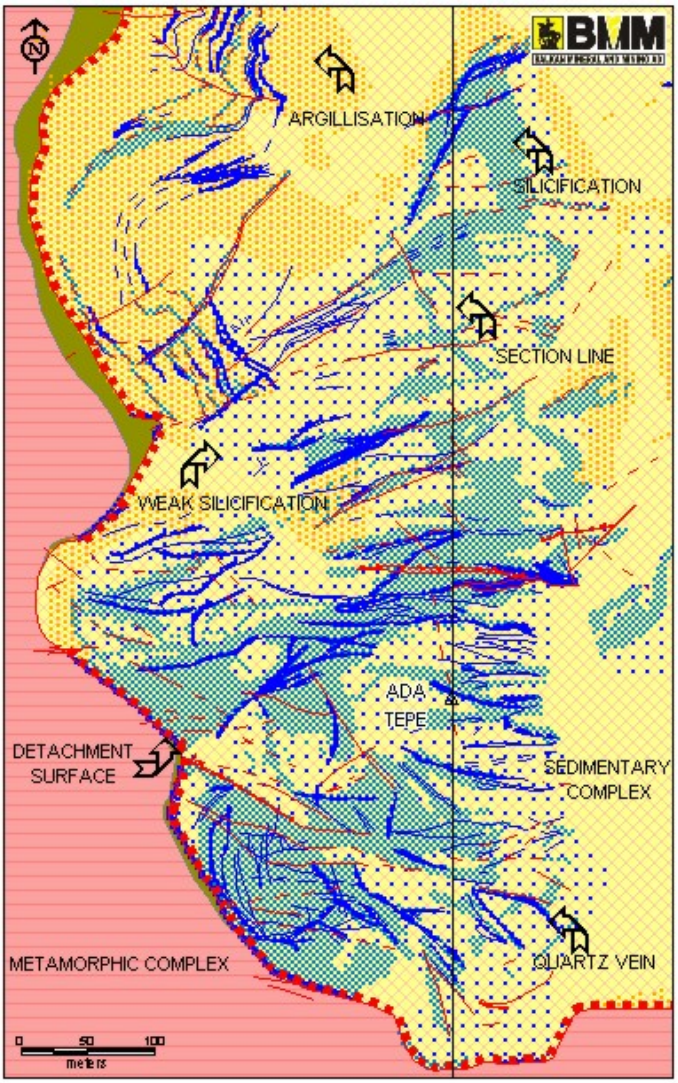
Mining: potential open pit mine.
Metals: Au, Ag.

Total resources: M&I 5.22 Mt of ore at 5.0 g/t Au for 835 000 ounces of Au, using a 1.0 g/t cutoff grade; and 440 000 ounces of Ag.
Type: Sedimentary-hosted low-sulphidation epithermal Au deposit.

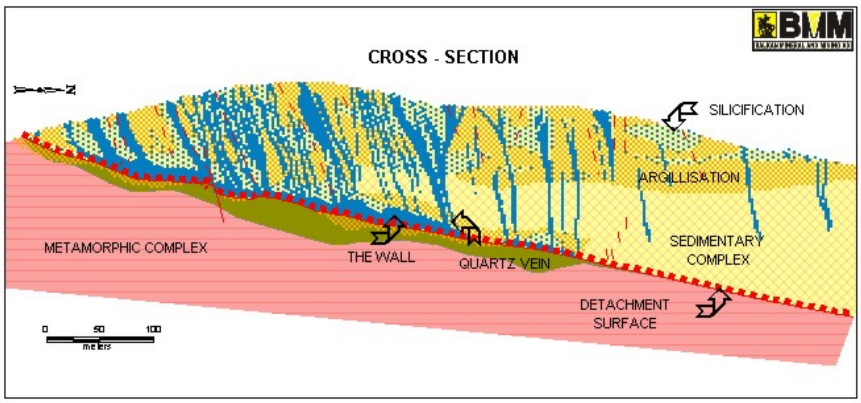
Structure: The dominant structure - low-angle normal fault, named Tokachka detachment fault, which is recognized as a contact between Paleozoic metamorphic rocks and Maastrichtian-Paleocene sedimentary rocks of the Shavarovo Formation.



Simplified geological map of the Eastern Rhodope showing position of the Ada Tepe Au deposit in respect to the Kessebir metamorphic dome and the major volcanic areas and dyke swarms



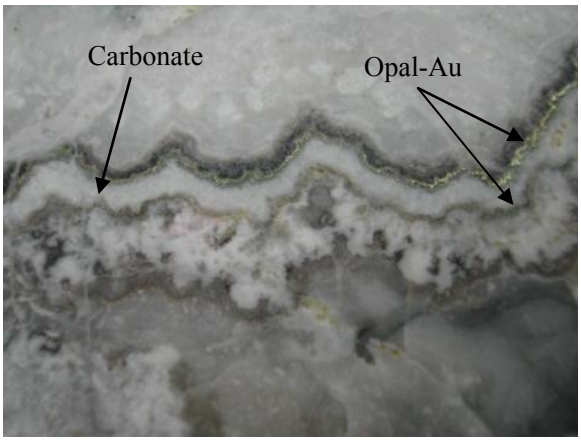
Unpublished geological map of Ada Tepe Au deposit, prepared by D. Jelev (BMM).



Cross section, line 613, of Ada Tepe deposit. Shown are: the massive, tabular ore body ("The Wall") above the detachment fault and vein ores along predominantly E-W oriented steep faults. Unpublished data of D. Jelev (BMM).

Ore geometry and ore bodies: 600 m along strike and 300-350 m wide. Mineralization occurs as: (1) a massive, tabular body (known as the "Wall") located immediately above the detachment fault, and (2) open space-filling within the breccia-conglomerate and sandstone along predominantly east-west oriented subvertical listric faults within the hanging wall.

Age of mineralization: Upper Eocene, 34.99 ± 0.23 Ma based on plateau age of adularia.
Ore minerals: electrum (73-76% Au), subordinate pyrite with traces of galena, and gold-silver tellurides



Bonanza Au mineralization of the Ada Tepe. Subparallel bands of microcrystalline silica+ adularia and electrum separated by a calcite vein

Alteration: Quartz, adularia, calcite, pyrite, dolomite-ankerite-siderite ± sericite, kaolinite.
Age of the host rocks: Maastrichtean-Paleocene.
Nature of host rocks: Supradetachment sediments (Shavarovo Formation), derived primarily from the underlying metamorphic complex.

Genesis: Sr and Pb isotope ratios are consistent with the idea that metals and carbonates were probably derived from the metamorphic basement rocks with a possible contribution from an igneous source. Collectively, structural, age and isotopic data suggest an intimate association of Ada Tepe Au mineralization to the metamorphic core-complex formation rather than to the local magmatism.
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