

A genetic model of the Elatsite porphyry copper deposit, Bulgaria

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Abstract. The Elatsite porphyry copper deposit is one of the two operating large Bulgarian copper and gold deposits. It is located in the Elatsite-Chelopech ore field, the northernmost part of the Panagyurishte ore district of the Apuseni-Banat-Timok-Srednogorie magmatic and metallogenic belt. The ore mineralization is associated with the Late Cretaceous magmatic activity manifested in the area. It is of vein-disseminated type and builds up a large ore stockwork. The basic industrial mineral is copper and secondary ones are gold and molybdenum. The deposit model reflects the evolution of magmatism, development of the hydrothermal system and tectonic events taking place during its formation. Two types of hydrothermal systems occurred: magmatic and magmatic-meteoric, the magmatic being the dominant one. The model designed reflects the zoning of hydrothermal alterations as well as the relationship between wallrock alterations and ore mineralizations which are relevant characteristics required for constructing the porphyry-copper models. This approach allowed the comparison of the model proposed with the basic models of porphyry-copper systems: Lowell-Gilbert's quartz-monzonite model and Holister's diorite model. It was found that the model of the porphyry system at the Elatsite deposit exhibits common characteristics with respect to the main wallrock alterations (K-silicate, sericitic (phyllitic) and propylitic) and mineralizations (pyrite, chalcopyrite, bornite, molybdenite, rarely gold) in the universal model constructed by Lowell-Gilbert. The moderately argillitic alteration, shown in the Lowell-Gilbert model between the zones of sericitic and propylitic alteration, is not represented in the Elatsite deposit.

Key words: genetic model, porphyry copper deposit, porphyry stage, epithermal stage, Elatsite, Bulgaria

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Георги Георгиев. Генетичен модел на меднопорфирното находище Елаците, България

Резюме. Меднопорфирното находище Елаците е едно от двете действащите големи български находища за добив на мед и злато. То е разположено в Елашко-Челопешкото рудно поле, което се намира в най-северните части на Панагюрския руден район - елемент от Апусени-Банат-Тимок-Средногорския магматичен и металогенен пояс. Орудяването е генетично свързано с горнокредната магмена активизация проявена в района. То е от жилково впръснат тип и изгражда един голям руден щокверк. Главен промишлен елемент е медта, а второстепенни – златото и молибдена. Моделът на находището отразява магмената еволюция, развитието на хидротермалната система и тектонските събития протекли по време на неговото формиране. Проявени са два типа хидротермални системи - магмена и магмено-метеорна, като магмената е доминираща. В изготвения модел са отразени зоналността на хидротермалните промени, както и връзката околорудни изменения – рудни минерализации, които са едни от най-важните характеристики при съставянето на моделите на меднопорфирни находища. Това позволи съпоставянето на предложения модел с основните модели на

меднопорфирните системи - моделът на Лоуел-Жилберт (“кварц-монзонитовият”) и “диоритовият модел” на Holister, при което се установи, че моделът на порфирната система в находище Елаците показва общи черти по отношение на основните околорудни изменения (К-силикатен, серицитов (филизитов) и пропилитов) и минерализации (пирит, халкопирит, борнит, молибденит, рядко злато) в изведения от Лоуел-Жилберт универсален модел. В находището не е представен умерено аргилизитовият тип изменение, показан в модела на Лоуел-Жилберт между зоните със серицитов и пропилитов тип изменение.

Introduction

The rising metal prices recently led to a new boom in searching for various genetic types of ore deposits. Bulgaria along with the other Balkan countries continues is a particularly attractive region for copper and gold exploration.

The Elatsite porphyry copper deposit is one of the two operating Bulgarian copper and gold deposits. This circumstance aroused the interest of a number of investigators who studied its geological setting and mineral composition. The ore mineralization is vein-disseminated and builds up a large-sized ore stockwork. Copper is the main industrial constituent and secondary ones are gold and molybdenum.

The exploitation of the deposit began in 1981 and until the beginning of 2007 the ore mined was 242 Mt with 0.390% Cu content and the metal extracted was 944 437 t Cu. The remaining inferred reserves as of 01.01.2007 were 114 Mt ore and 331 255 t metal at 0.388% copper content.

The interest of many researchers investigating the geological structure and mineral composition of the deposit have been engendered by its economical importance. Many interesting results by different authors have been published till this moment. Except for detailed exploration the deposit have been subjected to specialized mineralogical (Bogdanov 1987; Dimitrov 1973, 1974, 1988; Dimitrov & Koleva 1975; Tokmakchieva 1982; Petrunov et al. 1992; Petrunov & Dragov 1993; Dragov & Petrunov 1994, 1996; Strashimirov & Kovachev 1994; Eliopoulos et al. 1995; Tokmakchieva & Pazderov 1995; Popov et al.

2000b; Fanger in von Quadt et al. 2002; Strashimirov et al. 2002, 2003; Tarkian & Stribny 1999; Tarkian et al. 2003; Georgiev 2005, 2008; Kehayov & Bogdanov 2005), thermo-barometric (Strashimirov & Kovachev 1992; Fanger in von Quadt et al. 2002; Strashimirov et al. 2002, 2003; Tarkian et al. 2003; Kehayov et al. 2003), geochemical (Bogdanov 1987; Popov et al. 2003; Popov & Georgiev 2004), structural (Kalaidziev et al. 1984; Georgiev 2004; Petrov 2005), petrological (Kanazirski in Popov et al. 2000b; Kanazirski in Strashimirov et al. 2002; Kanazirski et al. 2002; von Quadt et al. 2002; Georgiev 2004, 2005; Georgiev unpublished data) and other investigations.

Despite the numerous investigations carried out so far no generalized model of the Elatsite porphyry copper deposit has been developed. The models proposed by Bogdanov (1987), Petrunov & Dragov (1993) and Kehayov et al. (2003) reflect only some basic characteristics of the porphyry copper system. In the deposit models mentioned above the zoning of hydrothermal alterations as well as the relationship between wallrock alterations and ore mineralizations have not been described, although these characteristics are important for the construction of models of porphyry copper deposits. Therefore, the authors could not take into account the individual characteristics of the deposit and compare their own models with the universal models of porphyry copper deposits, namely, Lowell-Gilbert's quartz-monzonite model (Lowell & Guilbert 1970) and Holister's diorite model (Holister 1978).

The model of the Elatsite porphyry copper deposit which we propose has been constructed

mainly on the basis of the obtained data on the geological and structural setting, petrographic features, wallrock alterations, ore mineralizations, physicochemical characteristics of the hydrothermal fluid, spatial position and morphology of the ore body with the ore content distribution in it and the geochemical peculiarities in the deposit.

Regional position

The Elatsite deposit is located on the northern slope of the Chelopeska Baba peak, about 55-60 km east of Sofia and 6 km south of the town of Etropole. The deposit formed within the Elatsite-Chelopech ore field in the northernmost parts of the Panagyurishte ore district.

Geotectonic and metallogenic position of the Panagyurishte ore district

The Panagyurishte ore district is located 55-95 km east of Sofia. Its territory comprises parts of Central Srednogorie and the Stara planina mountains between the towns of Pazardzhik and Etropole. The geological position of the Panagyurishte ore district is determined by the area of development of intensive Late Cretaceous magmatic activity in that region as well as the associated mineral deposits (Popov et al. 2000b).

Over 150 ore deposits, ore occurrences and mineral manifestations have been established in the Panagyurishte ore district. It is characterized mainly by porphyry copper and massive sulfide copper deposits. Small gold-ore, gold-polymetallic, barite, lead-zinc and manganese deposits and ore occurrences are also encountered. Alluvial gold-bearing placers have been found as well.

In terms of geology and metallogeny the Panagyurishte ore district is an element of the Apuseni-Banat-Timok-Srednogorie magmatic and metallogenic belt defined by Popov et al. (2000a, 2002). This belt can be characterized by the development of a complex of Late Cretaceous and plutonic rocks and the

associated mineral deposits of the porphyry-copper and high- to medium-sulfide massive copper and gold-copper ones are of greatest significance. It is one of the main tectonic zones within the Alpine Carpathian-Balkanide system. The belt has a specific arc-like structure, approximately 1000 km long and 30-120 km wide, which formed after the subduction of the Vardar paleo-ocean and the subsequent collision processes during the Late Jurassic and Early Cretaceous (Popov 1987; Berza et al. 1998; Popov et al. 2002). The rock associations composing the separated magmatic complexes refer to four petrochemical series: calcium-alkaline, toleite, subalkaline and alkaline.

Geological position and metallogeny of the Elatsite-Chelopech ore field

The Elatsite-Chelopech ore field comprises part of the Stara planina mountain in the area of the Baba peak (south of Etropole) as well as part of the Srednogorie in the area of the town of Zlatitsa and the villages of Chelopech, Karlievo and Tsarkvishte (Popov & Kovachev 1996; Popov et al. 2000b, 2001). It falls within the northern part of the Panagyurishte ore district. The spatial position and boundaries of the ore field are determined by the development of the Late Cretaceous Elatsite-Chelopech volcano-plutonic complex including the Chelopech volcano and the associated intrusive bodies.

The Elatsite-Chelopech ore field contains the largest gold-copper reserves in Bulgaria. They are concentrated in the Chelopech high-sulfidation gold-copper deposit and the Elatsite gold and molybdenum-bearing porphyry-copper deposit. A number of smaller deposits have also been established in the ore field such as the Karlievo porphyry copper deposit, the Vozdol vein gold-copper-lead-zinc deposit, the Negarshtitsa vein gold-pyrite deposit, the Dolna Kamenitsa vein gold-lead-zinc deposit, the Kashana barite deposit and a series of ore occurrences (Popov et al. 2000b, 2001).

Geology of the Elatsite deposit

Old Paleozoic low-metamorphic rocks (phyllites, quartz-sericitic schists), contact metamorphic rock (hornfels and knotty schists), the Carboniferous granitoid Vezhen pluton (314 ± 4.8 Ma – according to U-Pb studies of von Quadt et al. 2002), the Elatsite Late Cretaceous quartz-monzodiorite intrusive and numerous associated dikes crop out in the deposit area (Georgiev 2004) (Fig. 1, Fig. 2). The mineralization is spatially and genetically associated with the Elatsite Late Cretaceous intrusive (Kalaidziev et al. 1984; Bogdanov 1987; Dimitrov 1988; Popov et al. 2001). According to data from the U-Pb method (von Quadt et al. 2002) the duration of the Late

Cretaceous magmatism in the deposit continued within the range of 91.27-92.4 Ma and the life of the magmatic-hydrothermal system determined by Re-Os studies is within 91.98-92.47 Ma (Zimmerman et al. 2003).

Three main fault structures can be traced in the deposit area: Elatsite fault ($75-125^\circ$), Murgana fault ($110-155^\circ$) and Kashana reverse slip-overthrust ($\sim 90^\circ$) (Georgiev 2004) (Fig. 3 a, b).

The wall rock alterations are: propylitic, K-silicate, K-silicate-sericitic and sericitic (Table 1; Fig. 4) (Kanazirski in Popov et al. 2000b; Kanazirski in Strashimirov et al. 2002; Kanazirski et al. 2002; Georgiev 2005; Georgiev unpublished result).

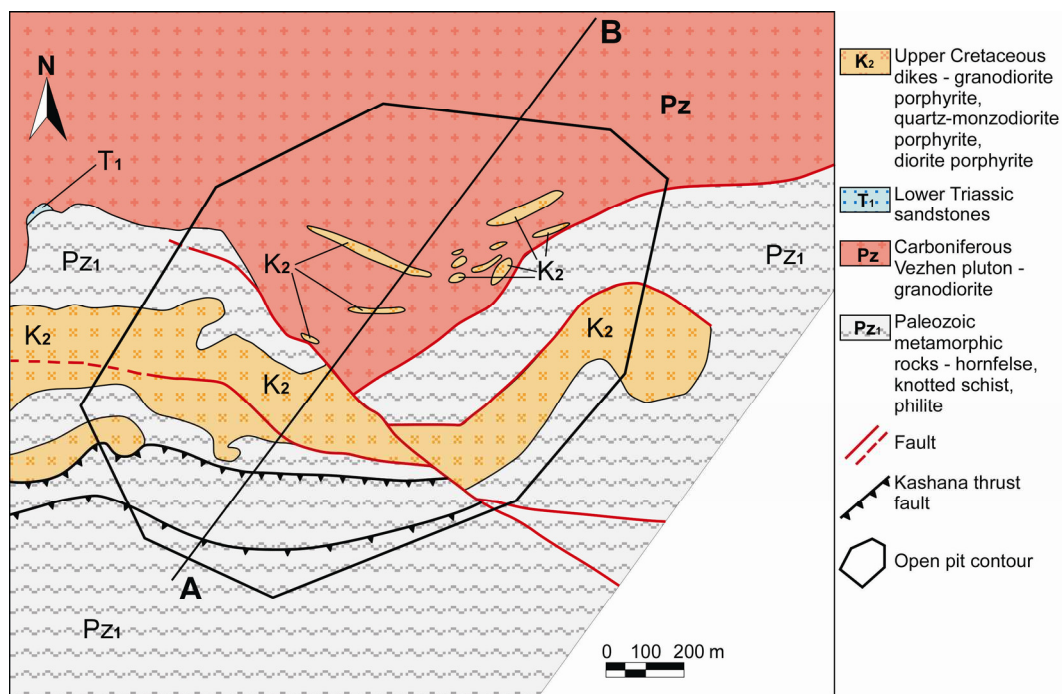


Fig. 1. Geological sketch map of the Elatsite deposit; (A-B) cross-section

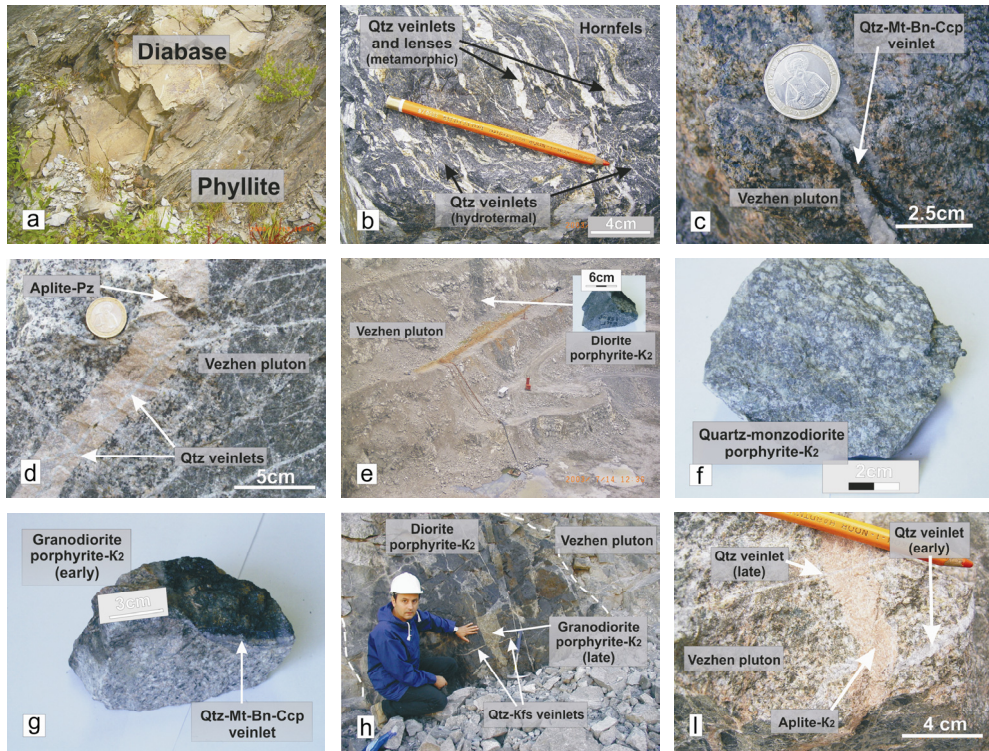


Fig. 2. a) diabase in phyllite from the deposit vicinity; b) metamorphic and hydrothermal quartz veinlets and lenses cutting hornfels; c) quartz-magnetite-bornite-chalcopyrite veinlet in the Vezhen pluton; d) Paleozoic aplite intruded in the Vezhen pluton and cut by hydrothermal quartz veinlets; e) Late Cretaceous microdiorite porphyrite, intruded in the Vezhen pluton; f) Late Cretaceous quartz-monzodiorite porphyrite; g) Late Cretaceous granodiorite porphyrite cut by quartz-magnetite-bornite-chalcopyrite veinlet; h) Late Cretaceous granodiorite porphyrite intruded in Late Cretaceous diorite porphyrite and cutting quartz-K-feldspar veinlets; i) relationship between Late Cretaceous aplite with early and late hydrothermal quartz veinlets. Abbreviations: (Bn) bornite; (Ccp) chalcopyrite; (Kfs) K-feldspar; (Mt) magnetite; (Qtz) quartz; (K₂) Late Cretaceous; (Pz) Paleozoic; (Qtz-Mt-Bn-Ccp) quartz-magnetite-bornite-chalcopyrite

Seven mineral assemblages have been identified in the deposit (Petrunov et al. 1992; Petrunov & Dragov 1993; Dragov & Petrunov 1994, 1996; Popov et al. 2000b; Fanger in von Quadt et al. 2002; Strashimirov et al. 2002, 2003; Georgiev 2005, 2008; Kehayov 2005). In the order of their formation these are: quartz-magnetite, quartz-magnetite-bornite-chalcopyrite, quartz-pyrite-chalcopyrite, quartz-molybdenum, quartz-pyrite, quartz-galena-sphalerite and quartz-carbonate-zeolite (Tab. 2, Fig. 5 a-g).

The quartz-magnetite, quartz-magnetite-bornite-chalcopyrite (Fig. 5h), quartz-pyrite-chalcopyrite assemblages are associated with the occurrence of K-silicate alteration (Georgiev 2005, 2008). The quartz-pyrite-chalcopyrite assemblage is also locally associated with propylitic alteration (Fig. 5i). Sericitic alteration occurs in the wall-rock of the quartz-pyrite veins (Fig. 5 e).

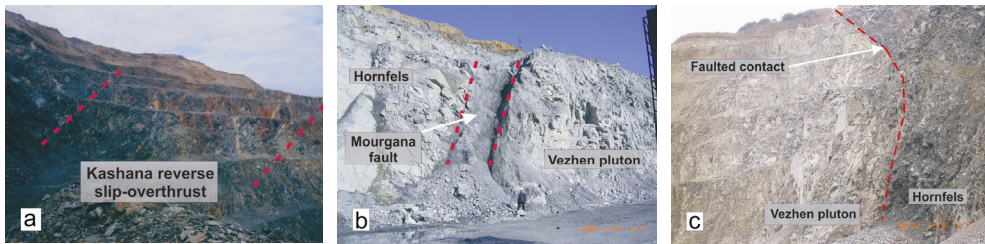


Fig. 3. a) Kashana reverse slip-overthrust; b) Murgana fault in the northern part of the open pit; c) Faulted contact between the Vezhen pluton and hornfels

Table 1. *Wallrock alterations and mineral assemblages in the Elatsite deposit (after Kanazirski et al. 2002). Abbreviations: (Ab) albite; (Act) actinolite; (Bi) biotite; (Cal) calcite; (Chl) chlorite; (Ep) epidote; (Ill) ilite; (Kfs) K-feldspar; (Py) pyrite; (Qtz) quartz*

Type of wallrock alteration	Mineral paragenesis
Propylitic	Ep + Act + Ab + Bt + Qtz + Cal Ep + Chl + Ab + Bt + Qtz
K-silicate	Kfs + Bt + Qtz + Il + Ab + Cal Kfs + Chl + Qtz + Il + Ab
K-silicate-sericitic	Chl + Ab + Qtz + Ill + Py Chl + Qtz + Il + Py
Sericitic	Ill + Qtz + Py

A geological model and development of the Elatsite porphyry copper system

Active magmatic activity began in the northern part of Panagyurishte ore district during the Late Cretaceous. A volcano-plutonic center has formed in depth in the area between Etropole and Chelopech (Popov et al. 2001). The originating melts have mantle genesis subsequently enriched in crustal material, borrowed from the overlying lithospheric layers of the Earth's crust (von Quadt et al. 2002; Stoykov et al. 2003). Host rocks for the Late Cretaceous dikes in the deposit area are granitoids of the Paleozoic Vezhen pluton, Old Paleozoic phyllites and contact-altered rocks: hornfels and knotty schists (Fig. 1).

The contact between the Vezhen pluton and the metamorphites (striking 60-80° and dipping to the southeast ~ 45°, Fig. 3c) as well as the Kashana reverse slip-overthrust (Fig. 1; Fig. 3a) played basic magma-controlling role in the Elatsite deposit. The first portions of magma which penetrated the deposit area had diorite composition. They intruded intensively the faulted sections of the Vezhen pluton, parallel to its contact with the metamorphic rocks. The composition of the following magma portions is highly alkaline thus forming quartz-monzodiorite-porphyrity dikes. They are embedded in the Vezhen pluton and the metamorphic rocks. The embedding occurred at the time when the small Elatsite intrusive formed. The latter is the bearer of the porphyry copper mineralization in the deposit. During its formation the related large amounts of magma penetrated the loosened zone of the Kashana reverse slip-overthrust.

In its movement upwards the magma grabbed fragments of host rock which can often be observed in the peripheral parts of the magmatic body. After the Elatsite intrusive was embedded in the deposit, magmas of higher acidic composition were introduced and dikes of granodiorite-porphyrity composition formed. The intrusion of these magmas had a multi-pulse character. They penetrated mainly faulted zones of the Vezhen pluton and later the already hardened and faulted Elatsite intrusive. Aplites were also embedded during the hydrothermal activity.

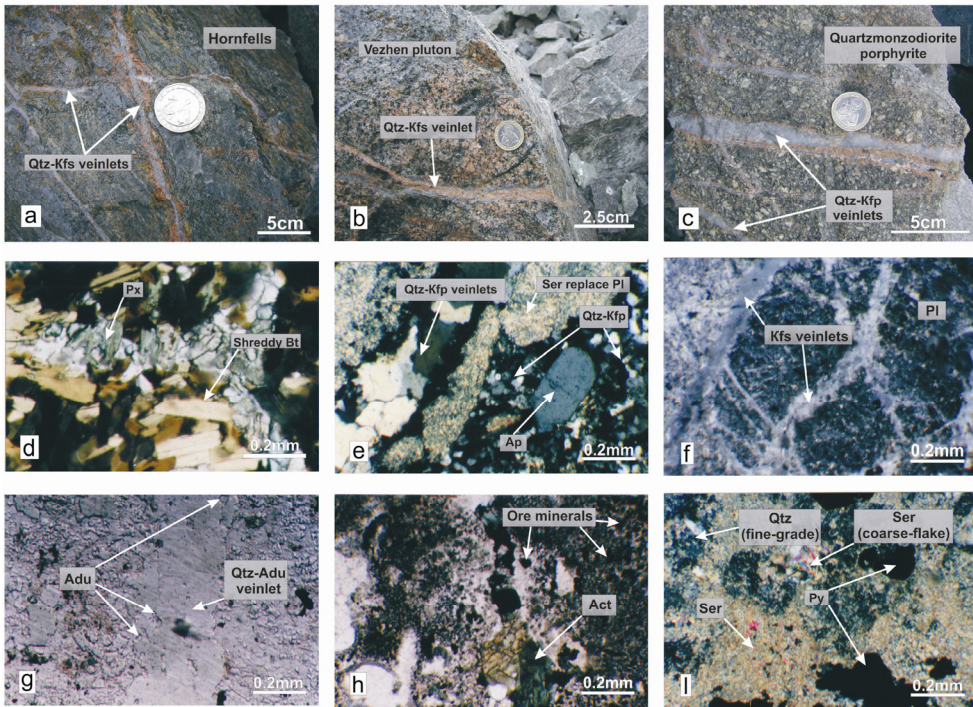


Fig. 4. Quartz-K-feldspar veinlets mark K-silicate wallrock alteration cutting hornfels (a), the Vezen pluton (b) and Upper Cretaceous quartz-monzodiorite porphyrite (c); K-silicate wallrock alteration on the contact between Upper Cretaceous granodiorite porphyrite and the Vezen pluton (d), in Upper Cretaceous quartz-monzodiorite porphyrite (e) and in the Vezen pluton (f), CPL image; g) propylitic wallrock alteration marked by adularite-quartz veinlet cuts Upper Cretaceous quartz-monzodiorite porphyrite, PPL image; h) propylitic wallrock alteration marked by actinolite veinlet in the Vezen pluton, PPL image; i) Sericitic wallrock alteration in quartz-monzodiorite porphyrite, CPL image. Abbreviations: (Act) actinolite; (Adu) adularia; (Ap) apatite; (Bt) biotite; (Kfs) K-feldspar; (Pl) plagioclase; (Py) pyrite; (Px) pyroxene; (Qtz) quartz; (Ser) sericite

The tectonic stress caused by the uprising magmas, the thermal field around them as well as the subsequent cooling have contributed to the intensive cracking and faulting of the host rocks. Numerous proto-cracks formed in them during the dike cooling. All that facilitated the infiltration of the hydrothermal solutions during the entire hydrothermal stage of mineralization in the deposit.

During the embedding of the Elatsite intrusive the magma produced stress in the host rocks thus forming a series of faults dipping ~ 35-50° with northern and southern vergence, respectively. The latter clearly intersect the

faults marking the Kashana reverse slip-overthrust.

Probably during the time of penetration of later portions of granitoid magma in depth, a big magmatic body was embedded beneath the deposit. Zones of axial symmetric load were created in its apical parts thus forming subvertical radially located faults and cracks in the deposit, part of which were later filled by ore veins (Fig. 6) (Georgiev 2004).

After the first dikes of granodiorite-porphyrity composition were intruded, intensive hydrothermal activity began. The Elatsite and Murgana subvertical faults as well

Table 2. Hypogenic minerals in Elatsite deposit (created by the author using data from: Dimitrov 1973, 1988; Bogdanov 1987; Petrunov et al. 1992; Petrunov & Dragov 1993; Dragov & Petrunov 1994, 1996; Strashimirov & Kovatchev 1994; Tokmakchieva & Pazderov 1995; Popov et al. 2000b; Strashimirov et al. 2002, 2003; Tarkian & Stribny 1999; Tarkian et al. 2003; Georgiev 2005, 2008; Kehayov 2005)

Hypogenic mineral assemblages	Minerals
Quartz-magnetite	quartz, magnetite
Quartz-magnetite-bornite-chalcopyrite	quartz, magnetite, bornite, chalcopyrite, molybdenite, tetrahedrite, tennantite, rutile, ilmenite, native gold, merenskyite, moncheite, carrollite, Ni-linnaeite, Cu-Ni linnaeite, pyrrhotite, clausthalite, hessite, kawazulite, naumannite, eucairite, bogdanowiczite, vaesite, michenerite, Se-michenerite (?), native Te, native Bi, petzite (?), stützite, sylvanite, wittichenite, uraninite
Quartz-pyrite-chalcopyrite	quartz, chalcopyrite, pyrite, Ni-Co pyrite, bornite, magnetite, hematite, tetrahedrite, tennantite, sphalerite, galena, molybdenite, carrollite, Cu siegenite, siegenite, marcasite, arsenopyrite, vaesite, palladoarsenide, Pd rammelsbergite, rammelsbergite, pararammelsbergite (?), electrum, emplectite (?)
Quartz-molybdenite	quartz, molybdenite, pyrite, chalcopyrite, electrum
Quartz-pyrite	quartz, calcite, pyrite, chalcopyrite, electrum
Quartz-Galena-Sphalerite	quartz, calcite, sphalerite, galena, pyrite, chalcopyrite, marcasite, arsenopyrite, freibergite, stephanite, argentite, electrum
Quartz-carbonate-zeolite	quartz, calcite, Mn-calcite, ankerite, dolomite, siderite, laumontite, stilbite, chabasite, heulandite

as the contact of the Vezhen pluton with the metamorphites in the NE part of the deposit played an ore-conducting role. The solutions were originally high-temperature, approximately 700°C (Tarkian et al. 2003) and the system can be defined as magmatic-hydrothermal. Strashimirov et al. (2002) emphasize the presence of CO₂ and CH₄ in two-phase high-temperature (>500°C) fluid inclusions. The presence of methane points to a magmatic source of hydrothermal solutions located at a great depth in the Earth's crust or even in the upper mantle.

The pre-ore hydrothermal rock alterations in the Elatsite deposit are associated with the intrusion of the early subvolcanic-hypoabyssal igneous bodies. Two main stages, typical for the porphyry copper deposits of the Panagyurishte ore district have been presented – porphyry and epithermal (Kanazirski in Strashimirov et al. 2002; Kanazirski et al. 2002). The porphyry stage of alteration and the first phase of development of the magmatic-hydrothermal system belong to the K-silicate type which affected all rocks in the deposit as well as the

less expressed propylitization. Intensive sericitization occurred during the epithermal development of the system with the participation of convection meteoric hydrothermal solutions in its upper parts (Fig. 7). The paragenetic data on a large number of porphyry copper deposits show that sericitization invariably develops after the K-silicate alteration and propylitization (Titley & Beane 1981).

Comparing the geological model of the Elatsite porphyry copper system with the two models of porphyry copper systems Lowell-Gilbert's quartz-monzonite model (Lowell, Guilbert 1970) and Holister's diorite model (Holister 1978) (Fig. 8), we found that it exhibits common features with regard to the main wallrock alterations (K-silicate, sericitic (phyllic) and propylitic) and mineralizations (pyrite, chalcopyrite, bornite, molybdenite, rarely gold) in the universal model deduced by Lowell-Gilbert. The moderately argillitic alteration, shown in the Lowell-Gilbert model between the zones of sericitic and propylitic alteration, however, is not represented in the Elatsite deposit.

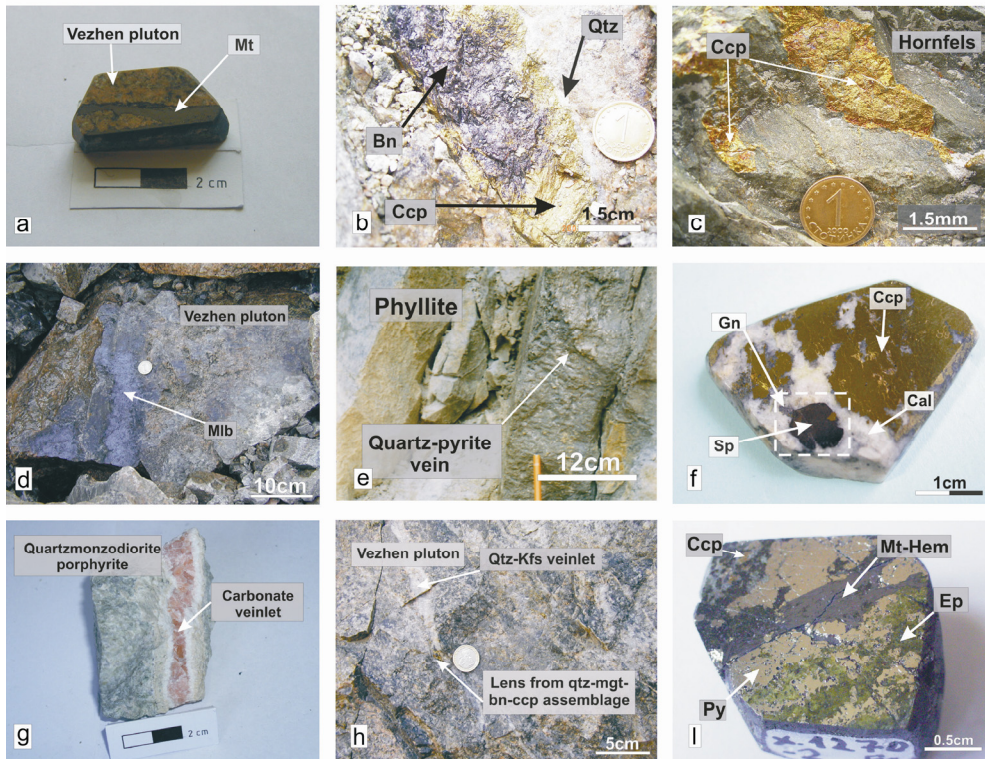


Fig. 5. a) quartz-magnetite assemblage – magnetite veinlet cutting the Vezhen pluton; b) lens of the quartz-magnetite-bornite-chalcocopyrite assemblage in the Vezhen pluton; c) the quartz-pyrite-chalcocopyrite assemblage – lenses and veinlets in hornfels; d) quartz-molybdenite assemblage – veinlet cutting the Vezhen pluton; e) quartz-pyrite assemblage – veinlet cutting phyllite; f) chalcocopyrite from the quartz-pyrite-chalcocopyrite assemblage and a nest of galena and sphalerite from the quartz-galena-sphalerite assemblage, soldered by calcite; g) zonal carbonate vein from the quartz-carbonate-zeolite association cutting quartz-monzodiorite porphyrite; h) relationship between the quartz-magnetite-bornite-chalcocopyrite assemblage and K-silicate wallrock alteration marked by quartz-K-feldspar veinlet; i) relationship between propylitic alteration marked by epidote and the quartz-pyrite-chalcocopyrite assemblage. Abbreviations: (Bn) bornite; (Cal) calcite; (Ccp) chalcocopyrite; (Ep) epidote; (Gn) galena; (Hem) hematite; (Kfs) K-feldspar; (Mlb) molybdenite; (Mt) magnetite; (Py) pyrite; (Qtz) quartz; (Sp) sphalerite

In his analysis of the problems of the hydrothermal rock alterations Taylor (1974) assumes that the magmatic-hydrothermal solutions were generated during the late stages of rock crystallization in the apical parts of the subvolcanic bodies and dikes and the meteoric-hydrothermal solutions circulated outside their boundaries. His assumption can possibly be applied to the Elatsite ore-forming system.

The two hydrothermal systems were active simultaneously at the early stages of development of the system. After the magmatic-hydrothermal system stopped to exist, the external meteoric-hydrothermal system continued to be active and when the heat source cooled, it moved into the zone of hydrothermally altered rocks formed under the action of the internal magmatic-hydrothermal

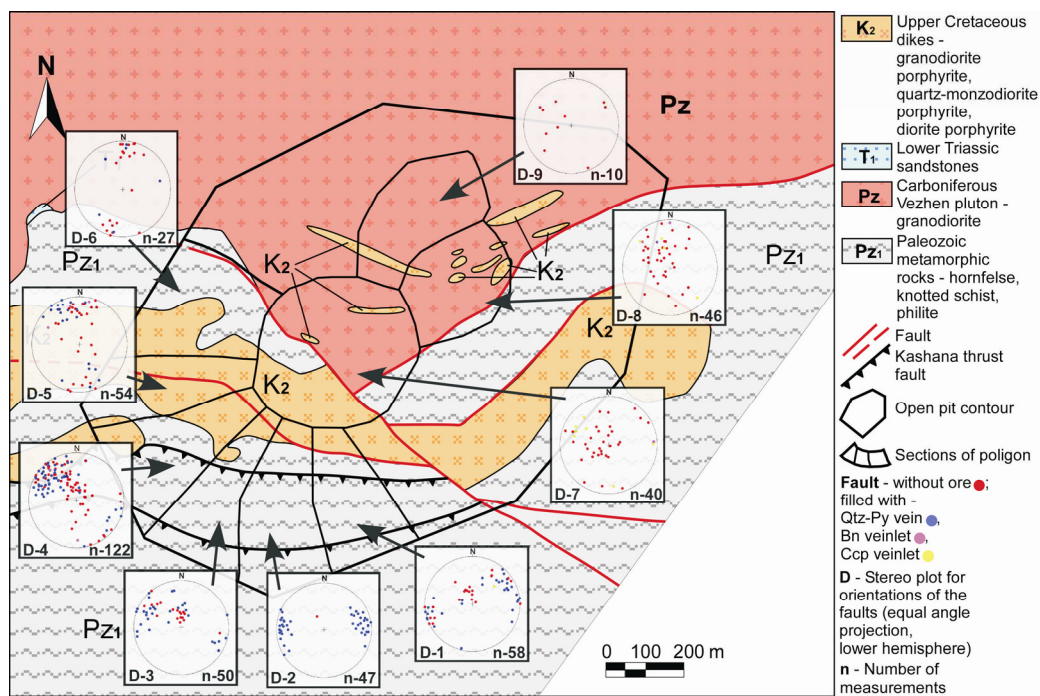


Fig. 6. Contoured stereo plots of fault measurements within the Elatsite deposit. Abbreviations: (Bn) bornite; (Ccp) chalcopyrite; (Py) pyrite; (Qtz) quartz

system. This led to local superposition of zones of sericitization on the rocks with K-silicate and propylitic alteration.

The porphyry stage in the development of the porphyry copper system

The mineral paragenesis K-feldspar + biotite, characteristic of the magmatic-hydrothermal K-silicate alteration, is in equilibrium with hydrothermal solutions of relatively high values of a_{K^+}/a_{H^+} . The high salinity of the inclusions in the minerals of the K-silicate alterations testifies for the magmatic origin of the solutions. Strashimirov et al. (2002) note that the K-silicate alteration was an initial stage of the development of the porphyry copper system in the Srednogorie region and occurred at a temperature of 500-550°C. The association

of magnetite and anhydrite with the early K-feldspar-biotite paragenesis is an indirect indication of increased oxyredox potential during its formation.

The propylitization within the development of the early K-silicate alterations and in the haloes around them was caused by the decrease in a_{K^+}/a_{H^+} and the related increase in acidity of solutions at temperatures in the interval 250-425°C. Chlorite and albite are permanently present in the mineral parageneses, typical of propylitization, in which we can also expect the participation of epidote, potassium feldspar, sericite, quartz, pyrite, sporadically calcite, actinolite, adularia, zeolites and prenite. As a rule, calcite which is characteristic of the propylitic paragenesis, is not represented or does occur sporadically

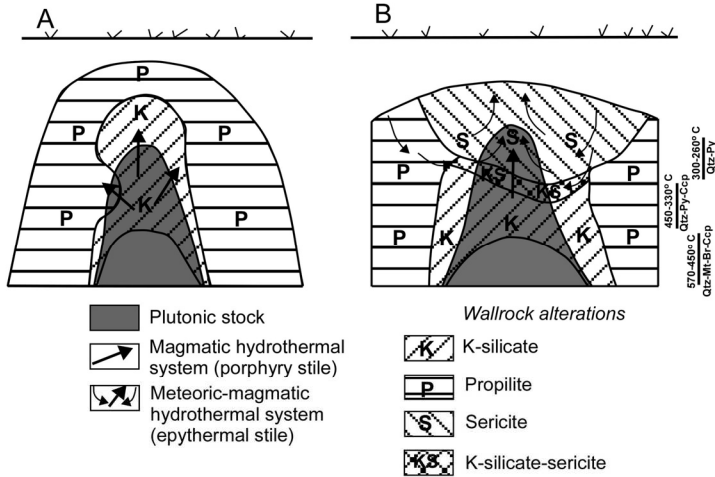


Fig. 7. Model of the wallrock alterations and main ore assemblages associated with the quartz-monzodiorite porphyry system in the Elatsite deposit. Development stages of the magmatic-hydrothermal system from porphyry (A) to a later epithermal (B) stage, associated to mixing of magmatic and meteoritic solutions. The spatial position of the main ore assemblages and the temperature of the solutions during their formation are shown on the left-hand side of the graphs. Abbreviations: (Qtz-Mt-Bn-Ccp) quartz-magnetite-bornite-chalcopyrite ore assemblage; (Qtz-Py-Ccp) quartz-pyrite-chalcopyrite ore assemblage; (Qtz-Py) quartz-pyrite ore assemblage

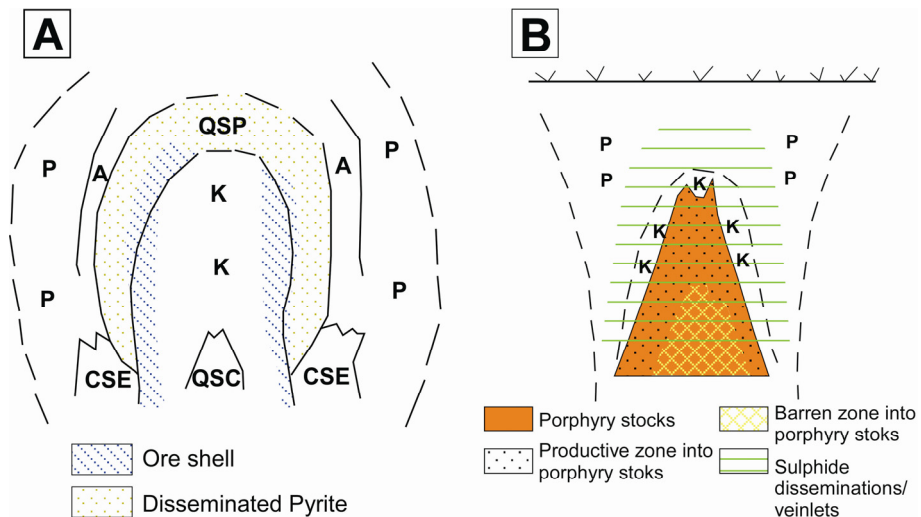


Fig. 8. A) Lowell-Guilbert models (after Lowell & Guilbert 1970) of alteration-mineralisation zonal patterns related to a quartz-monzonite porphyry system. Abbreviations: alterations – (K) potassic; (A) argillic; (QSP) phyllic-quartz-sericite-pyrite; (P) propylitic; (CSE) chlorite-sericite-epidote + magnetite; (QSC) quartz-sericite-chlorite ± K-feldspar; B) Diorite model (after Holister 1978)

in the Elatsite deposit. This implies a lower chemical potential of CO₂ in the hydrothermal solutions. The albite formation indicates higher a_{Na^+} and lower $a_{\text{K}^+}/a_{\text{H}^+}$ values.

Before the deposition of the first ore assemblage (quartz-magnetite), the rocks in the deposit were subjected to intensive K-silicate alteration which can be best observed within the boundaries of the Vezhen pluton, the Late Cretaceous dykes and hornfels. Metasomatic K-feldspar, biotite, chlorite, quartz, illite, albite and calcite formed. Besides, independent quartz-K-feldspar veins were deposited. The mineral assemblages for this type of alteration are: 1) K-feldspar + biotite + quartz + illite + albite + calcite; 2) K-feldspar + chlorite + quartz + illite + albite. The solutions are high-temperature with slightly acid character. A little later began the formation of the quartz-magnetite assemblage. It was deposited in the form of thin veins and small lenses, rarely larger lenticular bodies mostly in the NE parts of the deposit within the boundaries of the Vezhen pluton and hornfels. The interface between the pluton and the hornfels in this section of the deposit had a leading ore-conducting role in the assemblage formation whereas the Elatsite and Murgana faults were either not formed or did not yet play an active role in the hydrothermal process. The physicochemical conditions are characterized by low fugacity of O₂. Intensive K-silicate alteration has occurred in the rocks around the ore veins (Georgiev 2008).

Immediately after the formation of the first ore assemblage, the deposition of the next one followed: quartz-magnetite-bornite-chalcocopyrite. Veins, veinlets and lenses formed often superimposing the preceding assemblage. The main minerals in the assemblage are magnetite, bornite and chalcocopyrite. First chalcocopyrite, magnetite and bornite were deposited during its formation and then again chalcocopyrite in which inclusions of magnetite, bornite, tennantite, molybdenum and pyrrhotite can be observed. At that time a number of rare minerals were deposited, primarily Co-Ni tiospinels (represented by the series: linnaeite-zigenite-

carrolite), telluride and selenide (clausthalite, hessite, kawazulite, naumannite, eucairite, bogdanovichite, weissite, maiche-nerite, wittichenite, sylvanite, stutzite, em-pressite, Se-maichenerite (?), petzite (?)), native Au, Te and Bi among which there are PGMs in the form of merenskyite and moncheite (Petrunov et al. 1992; Tarkian et al. 2003). The assemblage formation conditions are low-sulfur and low-oxide. This explains the formation of Co-Ni tiospinels, telluride and selenide (Petrunov et al. 1992; Dragov & Petrunov 1996). The higher Te and Se content in the fluid results in a decrease in the Pd and Pt solubility and deposition of their own minerals (Petrunov et al. 1992).

The geochemical assemblages in the quartz-magnetite-bornite-chalcocopyrite assemblage are: Fe-Ti, Cu-PGE-Fe-Co-Ni-Te-Bi-Se-Au-Ag and Ag-Se ± Te, Bi (Strashimirov et al. 2002). This assemblage was deposited at a temperature of 575-450°C and extremely high salinity of 50 wt.% NaCl, the salinity system being H₂O-NaCl ± FeCl₂. The high assay grade of gold (967-896 ‰) in the assemblage (Petrunov et al. 1992; Tarkian et al. 2003; Georgiev 2005, 2008; Kehayov & Bogdanov 2005) also implies formation under hypothermal conditions (Petrovskaya 1973). The hydrothermal solutions continued to be low-acidic, the wallrock alterations associated with that assemblage being also the K-silicate ones (Georgiev 2008).

Before the beginning of the next stage, intensive cracking and faulting of the ore-hosting rocks occurred in the deposit. The subsequent portions of granodiorite-porphyrite magma were embedded in the highly faulted parts of the Elatsite intrusive and the Vezhen pluton. The dykes formed intersected the earlier quartz, quartz-K-feldspar and ore veins (Fig. 2h). Thin aplite veins were also intruded in the open cracks, mainly in the Vezhen pluton (Fig. 2i).

The rock faulting and cracking was followed by the deposition of the economically most significant quartz-pyrite-chalcocopyrite assemblage. The Elatsite and Murgana faults

began to play an active ore-conducting role. The temperature of the solutions drops down to 450-330°C. The salinity of the system is high. The salinity system is H₂O-NaCl-KCl to H₂O-NaCl (Strashimirov et al. 2002). The high grade of silver in the gold-silver phases in the assemblage (assay grade of gold - 784-766‰) (Dimitrov 1973; Tokmakchieva 1982; Strashimirov & Kovatchev 1994; Tarkian et al. 2003; Georgiev 2005, 2008; Kehayov & Bogdanov 2005) also implies formation under mesothermal conditions (Petrovskaya 1973).

The quartz-pyrite-chalcopyrite assemblage was deposited in the form of veinlets, disseminated minerals and nests through the entire orebody. During its formation it penetrated the area of quartz-magnetite-bornite-chalcopyrite assemblage thus enriching it in Cu, Au and Mo. The main ore minerals are chalcopyrite and pyrite, chalcopyrite being in larger quantities than pyrite. The secondary minerals observed are bornite and Ni-Co pyrite, and the rare ones are tennantite-tetrahedrite, sphalerite, galena, magnetite, hematite, molybdenite, zigenite, copper-zigenite, carolite, marcasite, vaesite, palladoarsenite, Pd-rammelsbergite, rammelsbergite, pararammelsbergite (?), electrum, arsenopyrite and emplectite (?). The geochemical assemblages in the quartz-pyrite-chalcopyrite assemblage are: Fe-Cu (± Mo, Au), Co-Ni, Ni-Pd-As, Pb-Zn-Ag (Strashimirov et al. 2002).

The conditions under which the formation of the quartz-pyrite-chalcopyrite assemblage took place were characterized by high fugacity of O₂ and S (Dragov & Petrunov 1994, 1996). Magnetite and bornite became unstable and have been replaced by pyrite and chalcopyrite while pyrrhotite is replaced by marcasite and chalcopyrite (Dragov and Petrunov 1994, 1996; Georgiev 2005, 2008). Part of Fe was redeposited in the form of hematite. The potential of As⁻ and Sb⁻ was increased thus forming primary and reactionary Pd- and Ni-Pd arsenides such as: palladoarsenide, Pd-rammelsbergite, rammelsbergite, pararammelsbergite (?), tennantite-tetrahedrite and Co-Ni sulfoarsenides of the gersdorffite-cobaltine

group (Dragov & Petrunov 1994, 1996).

The hydrothermal solutions continued to be low-acidic, the main wallrock alterations being the K-silicate ones. Apart from these, in the local sections of the deposit, mainly in the hornfels at the interface with the Vezhen pluton, propylitic alteration occurred in association with the minerals of the quartz-pyrite-chalcopyrite assemblage (Georgiev 2008) (Fig. 5 i). The mineral assemblages which characterize it are: 1) epidote + actinolite + albite + biotite + quartz + calcite; 2) epidote + chlorite + albite + biotite + quartz.

The next quartz-molybdenum assemblage was deposited at somewhat lower temperatures in the form of thin quartz-molybdenum veinlets. It is more widely spread in the peripheral parts of the deposit (Bogdanov 1987). The temperatures of the solutions during its formations were in the interval 360-310°C and the characterizing geochemical assemblage is Mo-Re (Strashimirov et al. 2002).

The quartz-molybdenum assemblage during deposition was very close to the preceding one and is also associated with K-silicate altered rocks.

The epithermal stage in the development of the porphyry copper system

When the magmatic hydrothermal solutions mixed with the convection meteoric solutions, the manifestation of the epithermal stage in the evolution of the porphyry copper system began. The sericitization following the K-silicate alteration in the mixed magmatic-meteoric hydrothermal system was realized as the temperature, a_{K^+}/a_{H^+} of the solution and a_{Na^+} , $a_{Ca^{2+}}$, $a_{Mg^{2+}}$ dropped. The acidity of the solution increased resulting in unstable feldspars which were transformed into sericite (illite). Sericitic alteration occurred mainly in the upper levels of the deposit and rarely in the lower levels near faulty and fractured zones. It is characterized by the formation of quartz, sericite (illite) and pyrite as well as small veins

of fine- to coarse-grained, often idiomorphic pyrite which actually marked the formation of the quartz-pyrite ore assemblage. This assemblage is associated with the deposition of Au-Ag phases in the form of electrum (Bogdanov 1987; Dragov & Petrunov 1994, 1996) or silver bearing gold (Kehayov & Bogdanov 2005) of no economic significance.

The meteoritic-hydrothermal fluids of the porphyry copper system have temperatures of 450° to 250°C and have been formed at a depth between 1 and < 0.5 km (Pirajno 1992). Sericitization is associated with solutions of low salinity and prevailing homogenization temperatures of the order of 250-350°C. The mineral paragenesis quartz + sericite + pyrite which is determining for the sericitic alteration shows extraction of most cations of bases (Na, Mg, Ca) from the minerals of the altered rocks and testifies for an increase in the acidity of solutions during the evolution of the porphyry copper system.

The solutions penetrating the lower ore body levels alter the metasomatites formed during the porphyry stage of development of the hydrothermal system. Where the alteration had not been completed, the transitory K-silicate-sericite wallrock alteration occurred. It is characterized by the following mineral assemblages: 1) chlorite + albite + quartz + illite + pyrite; 2) chlorite + quartz + illite + pyrite. The K-silicate-sericitic alterations can be observed very rarely in the upper levels of the deposit near the boundary of the Late Cretaceous dykes (Georgiev 2005; Georgiev unpublished results).

The temperature at which the quartz-pyrite assemblage was deposited, is 300-260°C and the geochemical association for this assemblage is $Fe \pm Au$ (Strashimirov et al. 2002).

The mixed magmatic-meteoritic hydrothermal system in the Elatsite is primarily magmatic. Among the wallrock alterations we

have not met the argillite alteration typical of the mostly meteoritic mixed system which is manifested in the Asarel porphyry copper deposit in Panagyurishte ore district (Kanazirski et al. 2002; Kanazirski in Strashimirov et al. 2002).

Figure 9 along cross-section line A-B (see Fig. 1) depicts the geological-structural setting, the wallrock alterations and mineralizations in the Elatsite deposit.

A quartz-galena-sphalerite assemblage formed in the most peripheral parts of the Elatsite deposit in the form of veinlets and nests of quartz with inclusions of sphalerite, intergrown with galena among which chalcopyrite, tennantite and small amounts of pyrite, marcasite, electrum, freibergite, stephanite and argentite can be detected (Bogdanov 1987; Georgiev 2005, 2008, Kehayov 2005). It was deposited at a solution temperature of 240-230°C, and the geochemical assemblage is $Pb-Zn-Ag \pm Se$ (Strashimirov et al. 2002).

The last mineral assemblage in the deposit is quartz-carbonate-zeolite. Calcite, ankerite, manganian ankerite, manganocalcite, dolomite and zeolites (stilbite, lomontite, habasite and heylandite) have been deposited in the form of stockwork veins (Bogdanov 1987; Georgiev 2005, 2008). Redeposited sulfides such as chalcopyrite and pyrite can be traced and in some places fluorite can be encountered. This assemblage was deposited at a temperature of the hydrothermal solution of 250-190°C (Strashimirov & Kovachev 1992).

The formation of the assemblage described above concluded the active hydrothermal activity in the deposit.

A large ore stockwork formed as a result of the ore-forming process which is elongated in the NE-SW direction (35-215°) (Kalaidziev et al. 1984). It has developed in the intensively fractured hornfels, Paleozoic granodiorite and Late Cretaceous dykes. The ore mineralization

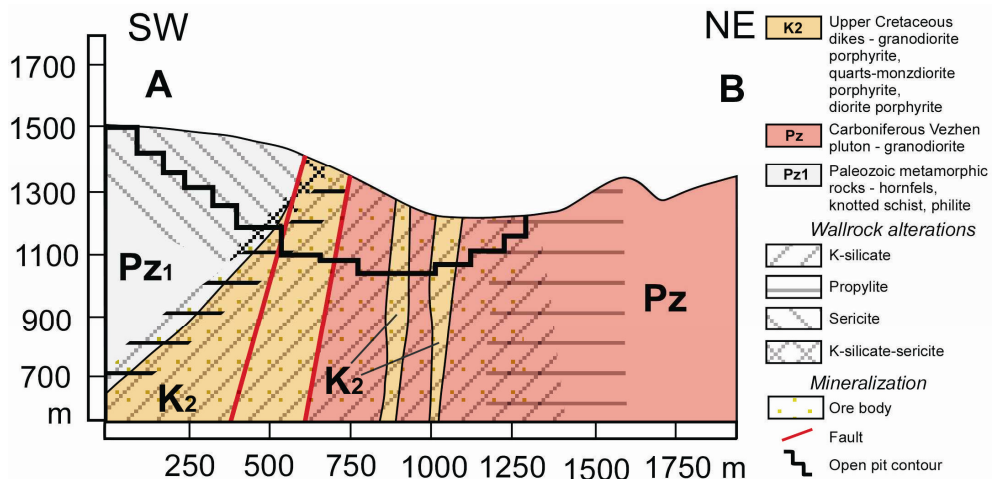


Fig. 9. Cross-section along the line A-B (see Fig. 1) in the Elatsite deposit

in the intrusive rocks is represented by numerous veinlets and disseminated minerals whereas in the metamorphites it consists mainly of veins. In horizontal plan view the ore stockwork is ellipsoid in shape, elongated in the northeastern direction (35°). It is 1200 m long and the width varies between 200 and 750 m. The area of its horizontal projection is approximately 0.616 km^2 . Its axis has a general dip of $35\text{-}50^\circ$ to the south and in principle follows the contact between the metamorphites and the Vezhen pluton. The ore stockwork is not outlined in depth because most boreholes have not reached its boundaries. It follows consistently its strike and dip. The boundary between the orebody and the host rocks is gradual. It is determined by the economic copper content limits. The transition is much faster in the metamorphites with moving away from their contact with the igneous rocks. In these rocks the ore mineralization has developed mostly in the hornfels whereas the knotted schists and phyllites, due to their plasticity, had a screening role during the ore deposition. The spatial regularities in the distribution of the Cu content and the orebody morphology are represented by a 3D model of the orebody (Popov et al. 2003). The

anisotropy derived by Cu has a complex morphology because of the complicated geological structure and different directions of the tectonic faults as well as the change in the direction of contacts among the wall rocks. As a whole, the changes in the copper contents are mostly smooth in the NE-SW direction whereas in the NW-SE direction we can observe the highest variability values. The 3D ore body model characterizes the upper levels of the deposit and the highest contents have been established between levels 1400 and 1200.

Post-ore tectonic events and supergene processes

As a result of the post-Late Cretaceous tectonics (Laramide, Pyrenean and Neotectonic) and the accompanying erosional processes, the northern and southern parts of the Elatsite-Chelopech ore field have undergone considerable vertical movements and deeply eroded (Popov et al. 2001).

Dextral strike-slip fault movements of approximately 150 m amplitude occurred along the Murgana fault and the southwestern block of the deposit fell to approximately 50-150 m

(Kalaidziev et al. 1984) thus dividing the Elatsite intrusive into two parts. Normal slip fault movements of small amplitude (8-10 m) occurred along the Elatsite fault. Post-ore tectonic movements can also be noticed along the faults marking the Kashana thrust fault causing displacement of the subvertical faults and quartz-pyrite veins in the upper deposit levels in the northern direction with approximately 2 m amplitude. Probably at the same time tectonic movements occurred along the contact surface of the Vezhen pluton with the hornfels in the NE part of the quarry. During the Neotectonic deformations the orogenic uplifting of Stara Planina and Sredna Gora mountains are made. The erosional processes at this time have formed contemporary relief in the region. The upper level of the ore stockwork (at elevation 1400 m before the mining operations began) has opened up on the surface.

During the weathering of the surface parts of the deposit supergene processes took place at a depth of 50-60 m. The zone formed is not of economic interest but is characterized by a great variety of minerals (Tokmakchieva & Draganov 1985). The predominant amounts are of the supergene minerals hematite, goethite and lepidocrocite. In smaller quantities are native copper, cuprite, tenorite, chalcantite, malachite and azurite. Rare supergene minerals are: chalcocite, jureite, digenite, covellite, bornite, zincite, maghemite, chalcotrichite, fluellite, chrysocolla, halloysite, brochantite, melanterite, linarite, halotrichite, thenardite, sphaerosiderite, chalcophyllite, andrewsite, keottingite, atelestite, libethenite, phosphuranylite and molybdite.

The model proposed is presently being successfully used in both the mining operations at the Elatsite deposit and in the exploration works in the Elatsite-Chelopech ore field. It can considerably contribute to the geological surveys in the Panagyurishte and other ore districts whose metallogenic characteristics are determined by the porphyry copper deposits.

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