Epithermal intermediate-sulfidation veins in the low-grade metamorphic rocks in the upper levels of the Elatsite porphyry copper deposit, Bulgaria

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Abstract. Three types of ore veins are observed in the low-grade metamorphic host rocks (phyllites, quartz-sericitic schists) of the Vezhen pluton in the upper part of the Elatsite porphyry copper deposit, differing in their strikes, dips and mineral composition. The low-grade metamorphic rocks are not affected by the granitoids of the Vezhen pluton. The hydrothermal alterations style is sericitic.

The quartz veins are subparallel and located everywhere conform to the general foliation trend in N-S direction. Their thicknesses vary from 1–2 to 25–30 cm. They are often flexed with the foliation. The main ore minerals are pyrite, chalcopyrite and pyrrhotite; galena and sphalerite occur seldom and arsenopyrite, idaite, native bismuth and aschamalmite are scarce.

The pyrite veins are N-S and NE-SW striking, steeply dipping 60–90° to E and have width from several centimeters to 40–50 cm. They crosscut the quartz veins. The main minerals are pyrite, chalcopyrite and quartz; arsenopyrite, native gold, tellurobismuthite(?) and unspecified Bi-Te and Ag-Te minerals occur in trace amounts.

The base metal veins crosscut the first two vein types. They are striking 60–90° and dipping 50–70° SE and S with thicknesses from 0.5 to 7 cm. At places they are conform to the foliation but crosscutting is also common. The main ore minerals are sphalerite, galena, native silver and members of argentian tetrahedrite-freibergite series. Stephanite and pyrargyrite are also widespread. Chalcopyrite, marcasite and pyrite are rare. Mooihoekite, cupropolybasite and allargentum are in trace amounts.

The geological setting, alteration style of the host rocks, main textures, mineral assemblages and composition of some minerals indicate that all three vein types are of intermediate-sulfidation style. The present results are crucial to develop a valid prospecting model and allow for the better planning of field, geochemical and geophysical explorations in the area of Elatsite deposit.

Keywords: Elatsite, hydrothermal veins, intermediate-sulfidation style, ore minerals.

Резюме. В горните нива на меднопорфирно находище Елаците в нискостепенните метаморфити (филити, кварц-серicitови шисти) от вместващите скали на Веженския плутон са установени 3 типа жили, различаващи се по посока, наклон и минерален състав. Нискостепенните метаморфити са хидротермално променени в серицитов фациал и не са засегнати от контактното въздействие на гранитоидите на Веженския плутон.

Кварцовите жили са субпаралелни и навсякъде са конформни на общия тренд на фолиация с посока С-Ю. Дебелината им варира от 1–2 до 25–30 см. Често те са огънати заедно с фолиацията. Главният минерал е кварцът, а баритът, карбонатите и флуоритът се срещат рядко. Главните рудни минерали са пирит, халкопирит и пиротин, по-рядко се срещат галенит и сфалерит, а арсенопиритът, идаитът, самородният бисмут и ашамалмитът са много по-редки.

Пиритовите жили са с посока С-Ю до СИ-ЮЗ, стръмно залягащи на изток под ъгъл 60–90° и дебелина от няколко до 40–50 см. Те пресичат кварцовите жили. Главните минерали са пирит, халкопирит и кварц. В малки количества се срещат арсенопирит, електрум, телуробисмутит(?) и неопределен Bi-Te и Ag-Te минерали.

Полиметалните жили пресичат първите два типа жили. Те са с посока 60–90° и затъват под ъгъл 50–70° на ЮИ до Ю, а дебелината им е от 0,5 до 7 см. На някои места те са конформни на фолиацията, на други я пресичат. Главните рудни минерали са сфалерит, галенит, самородно сребро и членове на редицата сребърен тетраедрит-фрайбергит. По-рядко се срещат стефанит и пираргирит. Халкопиритът, марказит и пирит се срещат рядко. В малки количества са наблюдавани мойхокит, купрополибазит и аларгентум.

Според геоложкото положение, тип хидротермална промяна на вместващите скали, главните текстури, минералните асоции и състава на някои минерали, и трите типа новоустановени жили могат да бъдат определени като умереносулфидидни. Тези резултати са важни за построяване на адекватен модел за проучване и за планиране на полевите, геохимичните и геофизичните изследвания в района на находище Елаците.

Ключови думи: Елаците, хидротермални жили, умереносулфиден тип, рудни минерали.
**Introduction**

Porphyry deposits are the world’s most important source of Cu, Au and Mo, and often contain significant quantity of Ag, Sn, Pt, Pd and W.

The porphyry copper systems develop at the convergent plate boundaries and include porphyry deposits centered on intrusions, skarn, carbonate-replacement, sediment-hosted gold deposits, high- and intermediate-sulfidation epithermal deposits. High-sulfidation epithermal deposits may occur in lithocaps above porphyry copper deposits, where massive sulfide lodes tend to develop in deeper feeder structures and Au±Ag-rich, disseminated deposits approximately within the uppermost 500 m. Less commonly, intermediate-sulfidation epithermal mineralization, chiefly veins, may develop on the peripheries of the lithocaps (Sillitoe, 2010). Commonly these deposits occur in continental margin and island-arc settings (Sillitoe, 1972, 2010; Cooke et al., 2005; Richards, 2011).

The Elatsite porphyry copper deposit is one of the two operating Bulgarian Cu and Au deposits. Numerous papers discuss its structure, mineralization, depositional conditions, source and timing of magmatism and mineralisation.

In the last years the open pit of the deposit is enlarged to S and SW and unexplored areas were revealed. In 2010–2013, a team led by Prof. Zhivko Ivanov undertook a detailed mapping and sampling of the high levels of the open pit. Three vein types with hydrothermal mineralization are observed in the low-grade metamorphic rocks which are outside the zone of contact impact of the Vezhen pluton.

The aim of this study is to present the new data concerning the ore mineralizations in the low-grade metamorphic host rocks of the Vezhen pluton in the area of Elatsite deposit.

**Geological setting of the Elatsite deposit**

The Elatsite deposit is located on the northern slope of the Chelopeshka Baba Peak, about 55–60 km East of Sofia and 6 km South of the town of Etropole.

It is situated in the Upper Cretaceous Banat-Srednogore tectonic zone. The deposit is part of the Elatsite-Chelopech ore field and occupies the northernmost parts of the Panagyurishte ore district (Fig. 1). Over 150 mainly porphyry and epithermal copper ore deposits and occurrences are known in this district. They are genetically connected with the Late Cretaceous magmatic activity (Bogdanov, 1987; Popov et al., 2000, 2003).

The ore deposits are hosted mainly in the Upper Cretaceous subvolcanic quartz-monzonitic to granodioritic intrusions (U/Pb age 91.5–92 Ma) and partly in Paleozoic low-grade metamorphic rocks and granodiorites of the Vezhen pluton (314±4.8 Ma) (Bogdanov, 1987; Petrunov et al., 1992; Popov, Kovachev, 1996; Popov et al., 2000; von Quadt et al., 2002; Tarkian et al., 2003; Strashimirov et al., 2003).

Four faults of different orientation have been distinguished in the area of Elatsite deposit as a result from deformation events within a broad kinematic right shifting fault system with regional character: NW-SE, E-W, NE-SW, N-S (Ivanov et al., 2004f).

The porphyry Cu-Au-PGE mineralization is controlled by NW-SE and NE-SW trending faults, and covers an area of about 1 km² and can be traced to a depth of about 800 m.

**Materials and analytical techniques**

The 1:500 scale mapping of the high levels of the open pit (over 1270 m) and sampling of drill core was undertaken in the period 2010–2013. More than 100 samples were collected and about 40 polished sections were prepared. The optical studies and microphotographs were performed on microscope Opton-Universal pol-U.

The chemical composition of minerals was determined in two electron microscopy laboratories. The analyzing system at the laboratory in Eurotest-Control EAD is JEOL JSM 35 CF with Tracor Northern TN-2000, accelerating voltage of 25 kV and sample current of 1.10⁻⁷ A. The standards and lines used for analysis were PbS – PbLα, ZnS – ZnKα, CuFeS₂ – CuKα and SKα; PbTe – TeLα; pure Ag and Co – AgLα, CoKα; Bi₂S₃ – BiLα; Sb₂S₃ – SbLα. Acquisition times for all elements were 100 s. The analytical device at the laboratory to the University of Mining and Geology, Sofia, is JEOL JSM-6010 PLUS/LA, and the analytical conditions are 20 kV accelerating voltage, 30 Pa pressure, and low vacuum. The Ag and Ag-bearing, Bi and Te-bearing minerals were analyzed at Eurotest-Control EAD. Pyrite, marcasite, pyrrhotite, galena and sphalerite were analyzed at University of Mining and Geology. Some analyses were duplicated on both devices. The results show satisfactory matching.

**Results**

Many researchers have studied the mineral deposition in the Elatsite deposit (Bogdanov, 1987; Petrunov et al., 1992; Dragov, Petrunov, 1996; Strashimirov et al., 2002, 2003; Kehayov et al., 2003; Georgiev, 2009). The mineral succession is divided in different mineral parageneses or mineral associations. Most succession schemes include quartz-magnetite, magnetite-borneite-

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chalcopyrite, quartz-molybdenite, quartz-chalcopyrite-pyrite, quartz-pyrite and quartz-galena-sphalerite parageneses. The first four parageneses occur in the central part of the deposit and are associated with pervasive potassic alteration (quartz-K-feldspar-biotite). The last two mineral parageneses are deposited in the upper and marginal parts and are associated with propylitic and phyllic-argillic alterations.

The operation of the open pit to S and SW exposed unexplored areas with 3 types of ore veins. The veins are hosted in the low-grade metamorphic rocks (phyllites and quartz-sericitic schists), have different strikes, dips and mineral composition. The low-grade metamorphic rocks are not affected by the contact impact of the granitoid of the Vezhen pluton. The hydrothermal alterations style is sericitic. The three types of veins are quartz veins, pyrite veins and base metal veins. The quartz and pyrite veins occur very often whereas the base metal veins are found only in a few parts of the open pit.

**Quartz veins**

These are subparallel veins and lenses located conform to the general foliation trend with N-S direction (Ivanov et al., 2011f, 2012f). The vein thicknesses vary from 1–2 to 25–30 cm. These are often flexed with the foliation. The main gangue mineral is quartz; barite, carbonates and fluorite occur rarely. Well-shaped pyrite, chalcopyrite and pyrrhotite, rare galena and sphalerite and the gangue minerals up to 3–4 cm

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in size are observed in the cavities. Arsenopyrite, idaite, native bismuth and aschamalmite are found only by optical microscope and electron microprobe. All ore minerals were analyzed using electron microscopy. The results are shown in Table 1.

**Pyrite** is the most common mineral and is deposited as euhedral to anhedral grains from several microns to massive aggregates. Most of them are solid and are rarely cracked. Some grains contain chalcopyrite inclusions and mixed chalcopyrite and idaite inclusions (Fig. 2a, b). The microprobe analyses established only Fe and S.

**Pyrrhotite** is deposited in cavities together with pyrite and chalcopyrite as latest mineral. It forms platy hexagonal crystals up to 0.5 cm. It contains rarely inclusions from arsenopyrite (Fig. 2c). The chemical composition is calculated to the formula Fe$_{0.94}$S$_{1.06}$. Kehayov (2005) has analyzed pyrrhotite from the early quartz-pyrrhotite paragenesis in the porphyry copper ore and applying the Co content of the coexisting pyrite and pyrrhotite he calculated depositional temperatures in the range 251–505 °C with maximum between 245 to 285 °C. These values put the initial temperatures of hydrothermal deposition, whereas the analyzed in this study pyrrhotite from the Elatsite deposit fit better to the formula proposed by Lévy (1965).

**Chalcopyrite** is a rare mineral in the veins. It occurs as subhedral grains from 50 to 150 µm in pyrite and in cavities in the quartz (Fig. 2a, b). The chemical composition of the mineral is similar to the theoretical.

**Idaite** occurs predominately in close intergrowths with chalcopyrite as numerous oval or irregular inclusions in pyrite up to 50 µm (Fig. 2b). These inclusions are rarely set up by idaite only.

Idaite is often a lamellar product of decomposition of bornite; the color of the both minerals is very similar and they could easily be confused (Ramdohr, 1980). Idaite in the quartz veins is probably a result from decomposition of bornite. This assumption is due to the chalcopyrite lamellas in idaite. In other inclusions chalcopyrite and idaite do not show intergrowths relations and in this case it is likely to be directly deposited from the hydrothermal solution.

Idaite was the subject of numerous controversies about its chemical composition and crystallographic properties. Yund (1963) proposed a general formula Cu$_{5.5x}$Fe$_x$S$_{6.5x}$ for the synthetic idaite-like phase, whereas Lévy (1965) suggested an ideal composition Cu$_x$FeS$_y$. Ottemann and Frenzel (1971) concluded that its composition varies from Cu$_x$FeS$_y$ to Cu$_y$FeS$_x$. The chemical compositions of idaite from the Elatsite deposit fit better to the formula proposed by Lévy (1965).

**Arsenopyrite** is deposited as inclusions in pyrrhotite in the form of single subhedral crystals up to 100 µm in size (Fig. 2c). The calculated chemical compositions were Fe$_{1.07}$As$_{0.82}$S$_{1.11}$ and Fe$_{1.07}$As$_{0.92}$S$_{1.09}$. Irregular grains with similar colors and sizes from 2 to 50 µm, but most often around 15–20 µm, were found in calcite by observation in back scattered electrons. The microprobe analyses revealed that all grains contain Bi. Based on microprobe data, native bismuth and aschamalmite are distinguished.

**Native bismuth** is deposited as single grains up to 50 µm, the most of them around 20 µm, in calcite in association with aschamalmite (Fig. 2d). The microprobe analyses revealed Fe (3.79 wt%) and Mn (0.63 wt%).

**Aschamalmite** was found as 10–15 µm grains in calcite (Fig. 2d). Besides Pb, Bi and S, the electron microprobe analyses indicated also some Fe and Mn. Both native Bi and aschamalmite contain some Fe and Mn and it is very likely that these elements had been trapped from the host carbonate. Therefore the recalculations of the chemical composition did not fit well to the theoretical formula (Table 1).

**Table 1**

**Microprobe analyses of the minerals from the quartz veins**

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Mineral</th>
<th>Elements (wt%)</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fe</td>
<td>Cu</td>
</tr>
<tr>
<td>1.</td>
<td>Pyrite</td>
<td>46.76</td>
<td>53.24</td>
</tr>
<tr>
<td>2.</td>
<td>Chalcopyrite</td>
<td>33.57</td>
<td>28.53</td>
</tr>
<tr>
<td>3.</td>
<td>Chalcopyrite</td>
<td>33.71</td>
<td>28.14</td>
</tr>
<tr>
<td>4.</td>
<td>Chalcopyrite</td>
<td>31.26</td>
<td>32.38</td>
</tr>
<tr>
<td>5.</td>
<td>Pyrrhotite</td>
<td>60.56</td>
<td>39.44</td>
</tr>
<tr>
<td>6.</td>
<td>Arsenopyrite</td>
<td>37.42</td>
<td>42.93</td>
</tr>
<tr>
<td>7.</td>
<td>Arsenopyrite</td>
<td>38.16</td>
<td>39.16</td>
</tr>
<tr>
<td>8.</td>
<td>Idaite</td>
<td>18.79</td>
<td>48.72</td>
</tr>
<tr>
<td>9.</td>
<td>Idaite</td>
<td>17.34</td>
<td>51.25</td>
</tr>
<tr>
<td>10.</td>
<td>Native Bi</td>
<td>3.79</td>
<td>0.63</td>
</tr>
<tr>
<td>11.</td>
<td>Aschamalmite</td>
<td>3.41</td>
<td>64.04</td>
</tr>
</tbody>
</table>

44
Mladenova et al. (2001) reported the presence of complex Bi mineralization in the Svishti Plaz gold deposit and divided 3 sub-associations. The earliest sub-association comprises native Bi, chalcopyrite, aschamalmite, Cu-Pb-Bi sulfosalts and bismuthinite-pekoiote. A breakdown of an ISS or primary complex bismuth sulfosalt(?) is suggested.

Pyrite veins

These are well differentiated with a 60–90° dip to the east, N-S to NE-SW strike and width from several centimeters to 40–50 cm. The pyrite veins crosscut the quartz veins.

The main minerals are pyrite, chalcopyrite and quartz. Arsenopyrite, native gold, Bi-Te (tellurbismuthite?) and unspecified Bi-Te and Ag-Te minerals were observed by means of optical microscope and microprobe analyses. Microprobe analyses of the minerals from the pyrite veins are shown in Table 2.

Pyrite commonly occurs as large (0.5 cm or more across) euhedral grains with sharp crystal edges and aggregates as earliest mineral in the veins. The late chalcopyrite infills the cavities in the pyrite aggregates and embraces the single pyrite grains (Fig. 3a).

Chalcopyrite occurs in close intergrowths with pyrite (Fig. 3a). Occasionally it contains single gold grains (Fig. 3b, c). The microprobe analyses did not indicate any trace elements in its composition.
Table 2
Microprobe analyses of the sulfide minerals from the pyrite veins
Таблица 2
Микросондови анализи на сулфидни минерали от пиритовите жили

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Mineral</th>
<th>Fe</th>
<th>Cu</th>
<th>Ag</th>
<th>Au</th>
<th>Te</th>
<th>Bi</th>
<th>As</th>
<th>S</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Chalcopyrite</td>
<td>31.59</td>
<td>32.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35.68</td>
<td>Cu(<em>{0.94})Fe(</em>{1.03})S(_{2.02})</td>
</tr>
<tr>
<td>2.</td>
<td>Chalcopyrite</td>
<td>31.72</td>
<td>32.60</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35.67</td>
<td>Cu(<em>{0.94})Fe(</em>{1.03})S(_{2.02})</td>
</tr>
<tr>
<td>3.</td>
<td>Native gold</td>
<td>22.31</td>
<td></td>
<td></td>
<td>77.69</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Au(<em>{1.31})Ag(</em>{0.69})</td>
</tr>
<tr>
<td>4.</td>
<td>Native gold</td>
<td>46.22</td>
<td></td>
<td></td>
<td>53.78</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Au(<em>{0.64})Ag(</em>{0.17})</td>
</tr>
<tr>
<td>5.</td>
<td>Tellurbismuthite(?)</td>
<td>8.36</td>
<td>3.01</td>
<td></td>
<td></td>
<td>38.65</td>
<td>41.59</td>
<td>8.40</td>
<td></td>
<td>Fe(<em>{0.69})As(</em>{0.35})Cu(<em>{0.10})S(</em>{1.11})</td>
</tr>
<tr>
<td>6.</td>
<td>Arsenopyrite</td>
<td>34.44</td>
<td></td>
<td></td>
<td>6.68</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fe(<em>{0.69})As(</em>{0.35})Cu(<em>{0.10})S(</em>{1.11})</td>
</tr>
<tr>
<td>7.</td>
<td>Arsenopyrite</td>
<td>34.02</td>
<td></td>
<td></td>
<td>7.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Fe(<em>{0.69})As(</em>{0.35})Cu(<em>{0.10})S(</em>{1.11})</td>
</tr>
<tr>
<td>9.</td>
<td>Unspecified mineral</td>
<td>32.67</td>
<td>22.70</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>16.01</td>
<td>28.58</td>
</tr>
<tr>
<td>10.</td>
<td>Unspecified mineral</td>
<td>15.19</td>
<td>5.69</td>
<td></td>
<td>32.86</td>
<td>8.35</td>
<td>13.00</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Native gold** occurs as oval or irregular grains up to 20 µm in chalcopyrite (Fig. 3b, c). Electron microprobe analyses revealed that the gold was always alloyed with Ag. The silver content in the two analyses is 22.31 wt% and 46.22 wt% respectively, which defines these compositions as electrum (Petrovskaya, 1973; Harris, 1990). The fineness 776.9 and 537.8‰ was calculated using the formula proposed by Harris (1990).

Native gold is common mineral for quartz-pyrite and quartz-galena-sphalerite assemblages of the porphyry copper ore at the Elatsite deposit (Bogdanov et al., 2005; Kehayov, 2005).

**Unspecified Bi-Te and Ag-Te minerals** occur as irregular fine inclusions in chalcopyrite (Fig. 3b, c, d). The small sizes make correct analyses difficult and hence a correct diagnostic. They always contain significant quantities of Cu, Fe and S apparently trapped from the host chalcopyrite. It is difficult to attribute with certainty their composition to any of the known compounds (Table 2).

We suppose very cautiously that some of them could be related to tellurbismuthite(?) with ideal composition Bi\(_{2}\)Te\(_3\) (Table 2, an. 5). Based on the optical properties and microprobe analyses, the irregular grains in chalcopyrite could be attributed to arsenopyrite despite the Cu content which is probably due to the host chalcopyrite (Table 2, an. 6, 7). It is difficult to refer the analyses from 8 to 10 on Table 2 to any certain mineral.

**Base metal veins**

The base metal veins crosscut the first two vein types and hence are the latest veins in the low-grade metamorphic rocks. These are striking 60–90° and dipping 50–70° SE and S. At some places they are conform to the foliation but crosscutting is also common. Their thicknesses vary from 0.5 to 7 cm. The minerals in these veins are deposited symmetrically to the host rock; the quartz is deposited on the contact with the host rock whereas the central parts of the veins are filled up mainly with sphalerite. Often the minerals are cataclasized.

The main ore minerals are sphalerite, galena, native silver and members of argentian tetrahedrite-freibergite series. Stephanite and pyrargyrite occur often also. Mooihoekite, cupro-polysylise and allargentum are in trace amounts.

**Sphalerite** is the most common mineral. It occurs as irregular grains and nests and it seems to be deposited first (Fig. 4a–d). Besides Zn and S, it also contains Fe and Ag (Table 3). The sphalerite is FeS-poor (1.95 and 2 mole percent FeS in both analyses) with Ag 0.94 wt% and 2.15 wt% respectively. Cadmium was found in one analysis only, in concentration of 0.69 wt%.

**Galena** is deposited as irregular grains or veinlets in quartz or embrace and cut the sphalerite (Fig. 4a,b,d). The electron microprobe analyses indicate that it contains systematically as trace elements Zn from 3.12 to 6.37 wt%, Ag in 2 analyses and Fe in one analysis (Table 3).

**Chalcopyrite** is less abundant than galena and sphalerite. It is deposited as irregular grains up to 150–200 µm in fractures and cavities in sphalerite together with the associated minerals (Fig. 4b, c).

**Marcasite** is scarce. It forms platy crystals up to 1–1.5 mm as entirely replacement of pyrrhotite (Fig. 4d). The lamellae, having a distinct cleavage parallel to their length, are oriented along the basal plains of the primary pyrrhotite. Numerous studies indicate this replacement phenomenon of pyrrhotite to both pyrite and marcasite. The optical properties of the platy
crystals are sufficiently distinct from pyrite. The platy marcasite pseudomorphoses exhibits a large amount of pore space which has preferred orientation relative to the parent pyrrhotite, which suggests that the mechanism of the transformation is of Fe removal (Fleet, 1978; Murowchick, 1992). It is assumed that marcasite forms predominantly at low pH or S–2 deficient by the transformation of pyrrhotite than direct from the hydrothermal solution (Qian et al., 2011).

**Pyrite** is minor mineral in the base metal veins and occurs in the quartz as grains up to 50 µm.

The Ag and Ag-bearing minerals in the base metal veins are native silver, stephanite, pyrargyrite, members of argentian tetrahedrite-freibergite series, cupropolybasite, allargentum and mooihoekite. They occur in close intergrowths in between and embrace or crosscut the sphalerite. Because of the small sizes all they were identified by means of microprobe analyses (Table 4).

**Native silver** is a new mineral for Elatsite deposit and it is the most common silver mineral. Its identification was facilitated by its low hardness and easy
Fig. 4. Microphotographs of the minerals from the base metal veins

a, close intergrowths between sphalerite, galena and quartz; b, galena, native silver, stephanite, tetrahedrite and chalcopyrite in cavities in sphalerite; c, native silver, tetrahedrite and chalcopyrite deposited in cracks in sphalerite; d, platy marcasite in cracks in sphalerite, galena and quartz

Abbr.: Ag – native silver; Chp – chalcopyrite; Gal – galena; Mar – marcasite; Py – pyrite; Qtz – quartz; Sph – sphalerite; St – stephanite; Tt – tetrahedrite

Фиг. 4. Микрофотографии на минералите от полиметалните жили

а – тясно прорастване между сфалерит, галенит и кварц; б – галенит, самородно сребро, стефанит, тетраедрит и халкопирит в празнини в сфалерита; в – самородно сребро, тетраедрит и халкопирит, отложени в пукнатини в сфалерита; д – плочест марказит в пукнатини в сфалерита, галенита и кварца

Съкр.: Ag – самородно сребро; Chp – халкопирит; Gal – галенит; Mar – марказит; Py – пирит; Qtz – кварц; Sph – сфалерит; St – стефанит; Tt – тетраедрит

<table>
<thead>
<tr>
<th>Nr.</th>
<th>Mineral</th>
<th>Elements (wt%)</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fe  Ag  S  Zn  Pb  Cd</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>Sphalerite</td>
<td>1.95 0.94 33.82 62.60 0.69</td>
<td>Zn_{0.93}Fe_{0.03}Ag_{0.01}Cd_{0.01}S_{1.02}</td>
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<tr>
<td>2.</td>
<td>Sphalerite</td>
<td>2.00 2.15 33.43 62.42</td>
<td>Zn_{0.93}Fe_{0.03}Ag_{0.02}S_{1.02}</td>
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<tr>
<td>3.</td>
<td>Galena</td>
<td>1.19 3.12 84.95</td>
<td>Pb_{0.92}Zn_{0.08}S_{0.88}</td>
</tr>
<tr>
<td>4.</td>
<td>Galena</td>
<td>3.00 11.85 3.25 81.89</td>
<td>Pb_{0.92}Zn_{0.08}Ag_{0.02}S_{0.88}</td>
</tr>
<tr>
<td>5.</td>
<td>Galena</td>
<td>0.41 4.44 12.37 6.37 76.40</td>
<td>Pb_{0.92}Zn_{0.08}Ag_{0.02}S_{0.88}</td>
</tr>
<tr>
<td>Nr.</td>
<td>Mineral</td>
<td>Fe</td>
<td>Ag</td>
</tr>
<tr>
<td>-----</td>
<td>-----------------</td>
<td>------</td>
<td>-------</td>
</tr>
<tr>
<td>1</td>
<td>Native silver</td>
<td>0.48</td>
<td>98.21</td>
</tr>
<tr>
<td>2</td>
<td>Native silver</td>
<td>0.47</td>
<td>98.55</td>
</tr>
<tr>
<td>3</td>
<td>Native silver</td>
<td>99.38</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Native silver</td>
<td>99.54</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Native silver</td>
<td>99.16</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Native silver</td>
<td>0.26</td>
<td>97.67</td>
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<tr>
<td>7</td>
<td>Native silver</td>
<td>0.21</td>
<td>98.54</td>
</tr>
<tr>
<td>8</td>
<td>Stefanite</td>
<td>0.14</td>
<td>69.03</td>
</tr>
<tr>
<td>9</td>
<td>Stefanite</td>
<td>0.12</td>
<td>69.32</td>
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<tr>
<td>10</td>
<td>Pyrargyrite</td>
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<td>62.02</td>
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<tr>
<td>11</td>
<td>Mooihoekite</td>
<td>24.07</td>
<td>17.40</td>
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<tr>
<td>12</td>
<td>Mooihoekite</td>
<td>29.09</td>
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<tr>
<td>13</td>
<td>Mooihoekite</td>
<td>25.80</td>
<td>5.90</td>
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<tr>
<td>14</td>
<td>Cupropolyhaseite</td>
<td>4.60</td>
<td>48.44</td>
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<tr>
<td>15</td>
<td>Cupropolyhaseite</td>
<td>5.18</td>
<td>54.33</td>
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<tr>
<td>16</td>
<td>Tetrahedrite</td>
<td>5.19</td>
<td>33.09</td>
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<tr>
<td>17</td>
<td>Tetrahedrite</td>
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<td>34.79</td>
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<tr>
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<td>Tetrahedrite</td>
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<tr>
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<td>Tetrahedrite</td>
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<tr>
<td>20</td>
<td>Allargentum?</td>
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<td>90.05</td>
</tr>
<tr>
<td>21</td>
<td>Allargentum?</td>
<td>86.28</td>
<td></td>
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</table>

Pb content (wt%) in analyses: 9 – 4.09; 13 – 1.20; 16 – 4.85; 17 – 0.50; 19 – 1.63

Pb съдържания (wt%) в анализи: 9 – 4.09; 13 – 1.20; 16 – 4.85; 17 – 0.50; 19 – 1.63
The composition of cupropolybasite from Elatsite is similar to this of the type sample but there are some differences also. Only the Cu content is almost in the same range, all other elements show deviations. The chemical formulas of the two analyses from the Elatsite deposit are calculated on the basis of 29 atoms and according to the structural results and the revised chemical formula proposed by Bindi et al. (2007a,b) (Table 4).

**Allargentum** is a new mineral for Elatsite deposit. It is observed as around 120 µm hexagonal crystals in association with the other Ag minerals (Fig. 5b). Allargentum is relatively rare mineral and there are two suggestions for its chemical formulae. Somanchi and Clark (1966) using X-ray powder diffraction confirmed the presence of the compound Ag₉Sb; this compound was verified by Cipriani et al. (1996). Petruk et al. (1971) defined allargentum as $\text{Ag}_x\text{Sb}$, with $x = 0.13–0.14$. The two analyses of allargentum in this study indicate contents of Ag 86.28 and 90.05 wt% and of Sb 6.95 and 13.02 wt% (Table 4). The presence of Fe and S is probably due to impurities.

**Members of argentian tetrahedrite-freibergite series** are deposited in close association with mooihoekite, stephanite and pyrargyrite in the space between the concentric zones of the colloform native silver; thus it also forms concentric bands with width around 10 µm (Fig. 5b). Argentian tetrahedrite-freibergite is a solid-solution series, which can be written $(\text{Cu, Ag})_{10}\text{Fe, Zn}_2\text{Sb}_{2}\text{S}_3$ (Ebel, Sack, 1991; Sack, 1992). The microprobe analyses reveal the typical elements for tetrahedrite. Ag ranges from 33.09 to 36.74 wt%, and Cu ranges from 14.06 to 15.13 wt%. The Fe and Zn content in individual grains is homogeneous and Fe content is generally higher than that of Zn. Arsenic content is variable from absence to 5.64 wt% (Table 4).
Freibergite was found by Bogdanov et al. (2005) and Kehayov (2005) in the quartz-galena-sphalerite assemblage in the porphyry ore of Elatsite magmatic-hydrothermal system.

*Mooihoekite* is deposited in the same spaces in the colloform native silver as members of argentian tetrahedrite-freibergite series. Its form and size are restricted by the space between the colloform bands but occasionally irregular grains occur, approximately 20 µm in size (Fig. 5a, b). It is deposited as fine-grained blebs in native silver as well (Fig. 3e). Under reflected light it has the color of chalcopyrite, but it tarnishes in air and is weakly anisotropic. Despite the significant differences of the chemical composition from this of the mooihoekite from the type locality (Cabri, Hall, 1972), we suppose with some reservation that the observed mineral is mooihoekite. The content 17.40 wt% Ag in one analysis could be attributed partly to the host native silver.
Discussions and conclusions

The understanding of porphyry-related ore systems is the result of analysing many mining and exploration cases around the world. Porphyry copper systems are defined as large volumes of hydrothermally altered rock centered on porphyry Cu stocks that may also contain skarn, carbonate-replacement and sediment-hosted deposits. According to most authors the shallower parts of the porphyry copper systems may host high- and intermediate-sulfidation epithermal Au±Ag±Cu orebodies (Kirkham, Sinclair, 1996; Corbett, Leach, 1998; Sillitoe, 1989, 2010; Hedenquist et al., 2000; Sillitoe, Hedenquist, 2003).

Comparison of the basic features of the two types of epithermal deposits in the porphyry copper systems shows considerable overlap in their characteristics. There are, however, many distinctive features as well.

High-sulfidation epithermal Au, Ag, and/or Cu deposits are typically located in the lithocap environment above the porphyry copper body. They contain sulfide-rich assemblages of high-sulfidation state, typically pyrite-ennargite, pyrite-luzonite, pyrite-famatinit, and pyrite-covellite, hosted by leached silicic rock with a halo of advanced argillic minerals (Hedenquist et al., 2000; Sillitoe, Hedenquist, 2003; Einaudi et al., 2003).

Intermediate-sulfidation epithermal precious metal deposits occur alongside lithocaps but typically spatially separate from the high-sulfidation orebodies and commonly do not show such a close connection with porphyry Cu deposits as do many of the high-sulfidation deposits (Hedenquist et al., 2000; Masterman et al., 2005). Intermediate-sulfidation epithermal deposits that are also sulfide-rich share many of the sulfide assemblages of high-sulfidation deposits, except that the enargite-bearing assemblage is lacking and the Ag:Au ratios are higher, at least 10:1, and typically >100:1. The major sulfide assemblage can be relatively simple, including combinations of FeS-poor sphalerite (from <1 to 10 mole % FeS, locally up to 20 mole % FeS), galena, pyrite, chalcopryte, and tetrahedrite but lacking appreciable arsenopyrite and pyrrhotite. Silver is present as Ag sulfosalts, and in some cases a large variety of these minerals occur in trace quantities. The main gangue minerals are Mn-bearing carbonates, rhodonite, and quartz (Hedenquist et al., 2000; Sillitoe, Hedenquist, 2003; Einaudi et al., 2003; Masterman et al., 2005; Sillitoe, 2010).

Besides the mineral composition the two epithermal deposits types differ by fluid compositions, salinity, pH, Eh, depositional temperature (White, Hedenquist, 1990; Arribas, 1995; Cooke, Simmons, 2000).

The three ore vein systems hosted by the low-metamorphic host rocks of the Elatsite porphyry copper deposit mark the low-temperature hydrothermal stage of the magmatic-hydrothermal system. They are cavity filling veins with sharp boundaries with the host rocks. The veins have distinct strikes, dips and mineral assemblages and all three types are hosted in rocks that are affected by sericite alteration. All three types are conform to the general foliation trend with N-S direction, what is due to the facilitation of fluids flow. Unlike quartz veins pyrite and base metal veins often crosscut the foliation also, what argue on their later deposition.

The quartz veins are deposited first. They are conform to the general foliation trend with N-S direction. The field observations indicate a symmetamorphic origin of the quartz veins. Their main minerals are pyrite, pyrrhotite and chalcopryte. Arsenopyrite, galena and sphalerite are scarce. Native Bi, iodite and aschamalnite are occasional. The gangue minerals are quartz, calcite and fluorite. Probably the veins (mainly their gangue component) are deposited during the metamorphic events. The sulfide minerals are deposited later in the same spaces.

The pyrite veins crosscut the quartz veins and are conform to the orientation of the generalised foliation trend and often they are flexed, boudinated and sheared. The main minerals are pyrite and chalcopyrite, the gangue is quartz. Native gold occurs rare in associations with complex and not well defined Bi-Te and Ag-Te compounds.

The base metal veins are deposited latest and occur only in some parts unlike the quartz and pyrite veins which are common. Most of them are conform to the foliation but the crosscutting is also frequent. Their common minerals are sphalerite and galena, whereas stephanite, pyrrargyrite, members of argentian tetrahedrite-freebergite series, native silver, chalcopyrite, pyrite and marcasite are less abundant. Allargentum, cupropolybasite and mooihoeekite occur rarely.

Based on the geological setting, alteration style of the host rocks, main textures, mineral assemblages and composition of some minerals it could be concluded that all three vein types are of epithermal intermediate-sulfidation style.

Some occurrences of apparently incompatible sulfide minerals are noted in the veins. Pyrrhotite is deposited as numerous crystals in cavities in the quartz veins occasionally with arsenopyrite. Pyrrhotite is not a defining mineral for intermediate-sulfidation deposits. Such occurrences may indicate appreciable but local fluctuations in sulfidation state during the lives of the system or, alternatively, that equilibrium was simply not attained (Giggenbach, 1992; Einaudi et al., 2003).

These results are crucial to develop a valid prospecting model and to allow planning of field, geochemical and geophysical explorations in the area of Elatsite deposit.

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References


