NEOGENE PORPHYRY SYSTEMS IN SOUTH APUSENI MOUNTAINS (ROMANIA): AN OVERVIEW

ION BERBELEAC¹, GAVRIL SĂBĂU², IOAN PINTEA², MARIA-LIDIA NUŢU-DRAGOMIR¹, SORIN SILVIU UDUBAŞA³, IOAN REFEÇ⁴

¹ "Sabba S. Ștefănescu" Institute of Geodynamics of the Romanian Academy, 19–21, Jean-Louis Calderon St., 020032 Bucharest, Romania
² Geological Institute of Romania, Bucharest
³ Faculty of Geology and Geophysics, University of Bucharest
⁴ MINEXFOR SA, Deva

Twenty porphyry copper systems have been identified so far in the South Apuseni Mountains, most of them within the Golden Quadrilateral area of the Metaliferi Mountains. They are genetically and spatially connected to multistage, shallow level Miocene intrusive complexes (andesite, quartz microdiorite) associated with pyroclastics and lava flows. The Miocene magmatic complex is discordant with respect to the pre-existing structures, its emplacement and location being controlled by extensional faults, coevally with small pull-apart basin formation. The spatial distribution of the subvolcanic magmatic conduits is constrained by the stress field and the flat-lying stratified structure of the basement. Extensive hydrothermal alteration is connected with ore deposition, as porphyry-style Cu-Au and Au-Cu disseminated ore, closely associated with epithermal veins and breccia bodies showing varying sulfidation degree, as the mineralizing fluids record important variations in temperature and composition. The main features of the 20 known porphyry Cu-Au deposits and prospects, varying in size from small to moderate, located mostly in the Golden Quadrilateral, but also in the adjacent Zarand and Poiana Ruscă Mountains, is given in a synoptic table. The present erosional surface opens different levels of the alteration and mineralization columns in individual porphyry and associated systems, exposing highly variable structures, from disseminations to breccia columns and epithermal veins.

Key words: Neogene, volcanic rocks, extensional regime, porphyry Cu-Au-Mo system, Apuseni Mountains.

1. INTRODUCTION

In Romania porphyry copper deposits/prospects are related to Alpine magmatic arcs. They are traditionally grouped in three provinces: Banat (South Carpathians), South Apuseni Mountains and East Carpathians. Ore generation occurred in two time periods: Upper Cretaceous – Eocene, in the Banat area, and Middle – Late Miocene, in the South Apuseni Mountains. This paper is focused exclusively on 20 Neogene known Cu-Au-(Mo) and Au-Cu-(Mo) porphyry-epithermal deposits/prospects dominantly situated within the Golden Quadrilateral area of the Metaliferi Mountains (Fig. 1), partially extending in the Zarand Mountains and towards NE of the Poiana Ruscă Mountains. From 20 deposits/prospects known, only two – Deva and Cireșata represent high-grade copper (0.2–0.4 g/t Au, 0.8% Cu) and, respective, gold (0.8 g/t Au, 0.2% Cu): an overview in terms of characteristics, distribution, grade and tonnage and tectonic control is given in Table 1. The rest of these deposits are low-grade Cu-Au (Mo) (~0.2–0.37 % Cu, 0.2–0.47 g/t Au).

Fig. 1 – The position of the Golden Quadrilateral (GQ) within Metaliferi Mountains. Thick black line – GQ, Dashed line – Roșia Montană–Bucium–Baia de Arieș District.
Table 1
Summary of main features of Neogene porphyry Cu–Au (Mo) deposits and prospects from South Apuseni Mountains.
Data from: 1 – Berbelae e & Andrei (1989); 2 – Berbelae e et al. (1995a); 3 – Per et al. (2001); 4 – Bojinescu (1984); 5 – Berbelae e (1980); 6 – Borcș & Berbelae e (1983); 7 – Nedel e et al. (2001); 8 – Andrei-Mayet et al. (2001); 9 – Kozmanov et al. (2003); 10 – Kun et al. (2012); 11 – Ruff et al. (2012); 12 – Hál e et al. (2010); 13 – Mu & Pirtea (2001); 14 – Berbelae e et al. (1982); 15 – Berbelae e et al. (2015); 16 – Berbelae e et al. (2016); 17 – Ciobânu et al. (2004); 18 – Popa et al. (1998); 19 – Chitlă cescu & Soocolaeu (1941); 20 – Cook & Ciobânu (2004); 21 – Iatan (2009); 22 – Ivićciaru & Roșu (2001); 23 – Iatan & Berbelae e (2018); 24 – Mu & al. (2004).

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<td>Kg-flysch;</td>
<td>Pg molasse; J epidotesite and rocks of island arc volcanics; Pre-Mz metamorphites</td>
<td>Bds-Sm volc.-sed. Fm, hb ox, hb-pz ox as pyroclastics, lavas and intrusions</td>
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<td>K&lt;sub&gt;2&lt;/sub&gt; felych; J ophiolites; Metamorphites</td>
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<td>unknown</td>
<td>unknown</td>
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<tr>
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<td>J ophiolites</td>
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<td>K2 fels;</td>
<td>J ophiolites</td>
<td>hb α, hb-qtz+py</td>
<td>K, Sr, Mg, Mn</td>
<td>unknown</td>
<td>2. Au-Ag ± bms</td>
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<td>1. ±?</td>
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<td>Măgura Sârani</td>
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<td>J ophiolites</td>
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<td>K, Sr, Mg, Mn</td>
<td>unknown</td>
<td>Probat Cu-Au porphyry structure</td>
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<td>unknown</td>
<td>K-fibs, Pr, Ser, Ad, Ar, Im ar</td>
<td>HS, IS, LS</td>
</tr>
<tr>
<td>Langa – Horia level 516</td>
<td>K&lt;sub&gt;2&lt;/sub&gt;-Pg molasse K&lt;sub&gt;2&lt;/sub&gt;-flysch J ophiolites Metamorphites</td>
<td>hb α</td>
<td>hb α, mēp</td>
<td>unknown</td>
<td>K-fibs, Pr, Ser, Ad, Ar, Im ar</td>
<td>HS, IS, LS</td>
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<td>Buciumi Tâmăța</td>
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<td>unknown</td>
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<td>Roșia Poieni</td>
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<td>hb α, nh mēp (Fundoaia type)</td>
<td>hb-bi α, brown hb ± px α (9.3 ± 0.50 Ma) as pyrocl. and small intr.</td>
<td>K-fibs, Pr, Ser, Ad, Ar</td>
<td>HS</td>
</tr>
</tbody>
</table>

**Pokana Rucără Mountains**

| Deva | K<sub>2</sub> sed.; Pz metamorphites | Bd-Sm detritite and cimetic rocks; hb α (12.2 ± 0.5 Ma) | bi-bi α (12.1 - 11.85 ± 0.5 Ma) | polymictic breccia type | K-fibs, Pr, Ser, Ad, Ar, Im ar | LS | bo-cp stockwork / like overthrust core | bo, cp, mt, py, Au, ce, cv, sp, gn | qtz – k-fibs – bt – cp – bo – mt – py; bo – cub – cp – po – cp, anhy – ze – ca | 13, 22 |

All 20 deposits/prospects are developed within and around porphyritic andesitic multi-stage intrusive complexes. Usually, these structures are hosts for hydrothermal depositions of Au-Ag-(Te), Au-As and Pb-Zn-Au-Ag-(Cu) ± Te veins and breccias. Numerous data about the Cu-Au-(Mo) porphyry deposits/prospects are provided in papers of Ionescu (1974), Ionescu et al. (1975), Ianovici et al. (1976, 1977), Vlad (1983), Boştinescu (1984), Berbeleac (1985, 1988, 2003), Berbeleac et al. (1985, 2012), Cioflica et al. (1995), Săbău et al. (2013) and others.

2. GEOTECTONIC AND GEODYNAMIC SETTINGS

The Apuseni Mountains represent a tectonic unit situated in the western part of Romania. They are divided into North Apuseni Mountains (NAM) and South Apuseni Mountains (SAM).

THE NORTH APUSENI MOUNTAINS (NAM)

NAM is built of several partly remobilized Variscan basement units composed of medium-grade metamorphic rocks and associated granitoids (~502–264 Ma), with Permo-Mesozoic sedimentary and volcanic cover (Stan, 1987; Dallmeyer et al., 1999; Pană et al., 2002; Seghedi, 2004). A system of Cretaceous nappes with north-verging thrusting (Bihor, Highiş – Drocea, Biharia and Muncel – Baia de Arieş) are grouped in Inner Dacides (Sândulescu, 1984, 2013). It extends up to 100 km between Highiş – Drocea Mountains and Gilău Mountains. In addition, a crustal shortening in Turonian followed in Senonian by a cease of the sedimentary processes within Gosau-type basin were events that affected the NAM tectonic evolution. NAM is argued to be separated from SAM through a Late Variscan shear belt (320–300 Ma) named Highiş – Biharia shear zone (Dallmeyer et al., 1999) composed of mylonitized granites and schists under low-grade metamorphic conditions.

THE SOUTH APUSENI MOUNTAINS (SAM)

SAM comprises the Drocea (DM), Metaliferi (MM) and Trascău (TM) Mountains (Fig. 2). They consist of Middle Jurassic ophiolites, Late Jurassic island arc calc-alkaline volcanic rocks (Savu et al., 1981) and Upper Jurassic – Upper Cretaceous sedimentary formations stacked as the Transilvanide nappes (Sândulescu, 1984). The nappe system from the western part of SAM (Groşi, Criş, Techereu – Drocea and Căbeşti (Lupu, 1972; Sândulescu, 1984; Bleahu et al., 1981) separate the Highiş crystalline (Biharia system) of NAM from the Supragetic nappe systems of the Poiana Ruscă Mountains. The eastern part of SAM roughly comprises the Feneş, Curechi – Stâniţa and Trascău (Bedeleu) nappes (Fig. 3).

The evolution of SAM contains an Upper Cretaceous – Paleocene “banatitic” magmatism (65–80 Ma, Ciobanu et al., 2004), which is focused along two lineaments: a N–S directed major lineament (Ștefan et al., 1992), which begins with the Banat granitoids and cuts across the Apuseni Mountains area (Drocea, Bihor, Gilău and Plopiş Mts.), consisting of intrusions (monzogranite, diorite, granite, andesite, dacite, lamprophyres), and volcano-sedimentary formations with andesite, dacite lava flows and ignimbrite rhyolites in the Vlădeasa Massif (Ștefan, 1980) and Plopiş Mts. (Borod – Corniţel), and a second one, a minor WNW–ENE – striking dioritic alignment in the central part of MM (Balşa – Techereu block – Berbeleac, 1975, 1977) and TM (Ștefan et al., 1992).

In SAM Maastrichtian – Paleocene (Borcoş et al., 1989), or Upper Cretaceous – Paleocene (Roşu et al., 2001) and Paleogene (Ciobanu et al., 2004) continental sedimentary deposits associate with andesites, rhyolites and rhyodacite tuffs, being well exposed in Vălişoara – Săcărâmb (Berbeleac, 1975) and Zlatna areas, formerly considered Tortonian (Ghiţulescu, Socolescu, 1941), or Helvetian (Cioflica et al., 1966).

In SAM the alpine basement is built up by Jurassic ophiolites, island arc volcanics and Cretaceous rocks folded and thrust within “Mid-“ and Upper Cretaceous nappe piles (Bleahu et al., 1981; Sândulescu, 1984, 1988; Ianovici et al., 1976; Balintoni, 1994, 2003; Balintoni and Vlad, 1998; Berbeleac, 2003). The pre-Alpine metamorphic basement underlies the nappe pile. The Jurassic ophiolites and island arc volcanic units mainly strike E–W (Berbeleac, 1970, 1977; Ciobanu et al., 2004); contrasting
with the N–S – directed main Upper Cretaceous – Paleogene magmatic lineament (Banatites) extending into the Plopiș and Bihor Mountains in NAM (Berbeleac et al., 1983; Ștefan et al., 1986) and South beyond the Danube River, in eastern Serbia (Cioflcă et al., 1995). The pre-Neogene magmatic activity, geodynamic evolution of blocks and crustal faults controlled the distribution and the intensity of Neogene sedimentation and magmatic and metallogenetic activity. An extensional lithospheric regime persisted throughout these Neogene events (Balintoni and Vlad, 1998; Berbeleac, 2003; Berbeleac et al., 2014).

![Fig. 2 – Geological map of Metaliferi and South Apuseni Mountains (from Berbeleac et al., 2014).](image)


![Fig. 3 – Tectono-structural map of central and southern part of the Apuseni Mountains (acc. to Sândulescu, 1984).](image)

THE NEOGENE – QUATERNARY DEPOSITIONAL EVOLUTION

The Tertiary evolution of the SAM area corresponds to a restless tectonic regime associated to extensive deformation occurring within the Tisia block (Csontos, 1995) and the Transylvanian unit (Sândulescu, 1984). Successive compression–extension events especially occurred along the contact between SC and SAM, reflected partially in the South Transylvanian Fault systems (Sândulescu, 1984) and Hâlmaciu – Brad – Sâcărâmb volcano-tectonic basin. As a consequence of these events, the metamorphic basement and/or ophiolites and their Mesozoic and Lower – Middle Miocene cover deposits underwent a great variety of deformations as rifting, faulting and graben formation in small pull-apart basins (Berbeleac, 2003; Berbeleac et al., 2012a, b, 2014). Probably partly, if not entirely, caused by Miocene (14–12 Ma) rapid clockwise rotation of the Tisia block (~60°, Pâtraşcu et al., 1994 and Panaiotu et al., 1998). This setting favoured the development of Miocene (14–7.4 Ma) to Quaternary (1.6 Ma, Roşu et al., 2004; Seghedi, 2004; Seghedi, Downes, 2011) dominantly andesitic, calc-alkaline, partly adakite-like volcanism and Miocene related mineralizations.

The Neogene sedimentation began with the Paleogene Faţa Băii Formation (Ciobanu et al., 2004; Fig. 2), previously considered also Tortonian (Ghiţulescu, Socolescu, 1941), Eocene (51.2±1.5 – 34.4±1.5 Ma K–Ar age; Lemne et al., 1983), Maastrichtian–Paleocene (Borcoş et al., 1989, 1998). The Faţa Băii Formation is of a continental volcano–sedimentary type, which consists usually of polymictic conglomerates (Faţa Băii type) with intervals of clays, sandstones, gravels (Almaşul Mare type) and some sequences of rhyolite and rhyodacite tuffs and andesite pyroclastics and lavas intercalated within the sediments. This formation is encountered in all intramountaineous volcano–tectonic basins of SAM, with its most typical representative the Hâlmaciu – Brad – Sâcărâmb basin (Berbeleac, 1975). A volcano–sedimentary sequence Volhynian in age, with globigerine marls reflects the passing from marine-pelagic to a marine–lacustrine regime. Sedimentation continues with gypsum clays, gypsum lenses being characteristic, andesite and dacite pyroclastics (breccias, tuffs), tuffs, volcanic conglomerates, dominantly hornblende quartz andesites in the Hârtaşgani – Sâlişte (Cioflica et al., 1966) and Almaşul Mare – Zlatna areas (Borcoş, Vlad, 1994), known as Dealul Cornilor Formation. This formation is coeval with similar volcano–sedimentary deposits from ZM, and MM (Hâlmaciu – Brad – Sâcărâmb basin). The Dealul Cornilor Formation in Hârtaşgani – Sâlişte area (e.g., Valea Rea, Valea Momeasa – Berbeleac, 1975) supports Upper Badenian – Lower Sarmatian sediments built up of siderite sandstone, marl, black clay, cineritic sandstone, cineritic andesite, polymictic conglomerate, and Leitha limestone. According to Sanders (1998) and Seghedi (2004), from Pliocene to Present, the AM suffered a continued erosion (ca. 1000 m) that correspond to isostatic uplift of 300–500 m.

TECTONIC EVOLUTION

The terrains from ZM and MM both recorded a component of extensional tectonics. Extension occurring during Upper Jurassic – Paleocene indicates similarities in the geometries of early extensional architectures. This means that similar processes acted in these areas, including stress and strain partitioning controlled by competency contrasts in the basement rocks, rapid vertical movement, inversion of sedimentary or volcano–tectonic basins in deep-reaching extensional faults, and the formation of a stratigraphic plate overlying the host stratigraphy. During the Miocene, areas of MM and ZM were affected by reactivation of large faults as crustal-scale extensional or shelf-edge faults. Probably these tectonic zones were parts of the thin-skinned thrust system; some of these were major basin-bounding faults. Relationships between rapid uplift and associated exhumation and the development of mineralizations have been discussed by numerous authors (e.g. Sillitoe, 1998; Berbeleac, 2003). These processes promote generation of overpressuring and fracturing and/or brecciation followed by discharge of magmatic fluids and rapid reduction of the confining pressure. The rapid fracturing enabled
for fluid hydraulic connection and fluid – fluid or fluid – wall-rock interaction. In addition, rapid fracturing produced large gradients in fluid temperatures, pressure, and chemistry, which lead to metal precipitation by phase separation. It appears reasonable that during the Middle Miocene in MM and ZM the porphyry and epithermal systems were formed by several cycles of intrusion and alteration within about 1–1.5 Ma. This is consistent with a model relying on magmatism and resulted fluids being connected with small episodes of movement along the sets of older and reactivated E–W and NE–SW crustal faults, and new NW–SE lineaments. Figure 2 shows the location of Middle Miocene Cu–Au–(Mo) porphyry and epithermal deposits and prospects as well as Upper Jurassic – Lower Cretaceous back-arc basin (marine sedimentation) in which the inversion of the back-arc extensional architecture played an important role in controlling the development of porphyry and epithermal systems in SAM.

The classical model of Sillitoe (1998) identified five features of compressional regimes that are considered ideal for the formation of the porphyry copper deposits: 1) inhibiting volcanism by compression that impedes magma ascent in the upper crust (e.g., Mc Clay et al., 2002; Cooke et al., 2005); 2) large shallow magmatic chambers; 3) volatile saturation of fractioned magma chambers and generation of magmatic-hydrothermal fluids; 4) compression restricts the number of apophyses on the roof of magma chamber and 5) rapid uplift of magmatic-hydrothermal fluids to abrupt decompression (e.g., Masterman et al., 2005).

Alternatively, according to Mathur et al. (2000) and Hill et al. (2002), the extensional regime may be favorable for the formation of steep, deeply penetrating faults reaching the lower crust or mantle where primitive magmas rich in metals are generated. On the other hand, the steep discontinuities favour the generation of steep conduits along which magmas and fluids undergo a rapid ascent without important loss of heat and volatiles. In MM and ZM (Berbeleac et al., 2010, 2012, 2015), as in Papua New Guinea and Chile (Gow and Walshe, 2005), the flat-lying stratigraphic plates such as the Transylvanide nappe system (Sândulescu, 1984) may play a key role in controlling the formation and distribution of deposits. Trapping and halting of magma ascent can be caused by impermeable flat-lying stratigraphic boundaries. This feature is manifested in SAM, in general, and especially in the Voia structure. These conditions lead to fractionation of magma and exsolution of its components. The distribution of effective stress creates overpressuring and related tensional fracturing that provides the main pathways for ore forming fluids from porphyry-magmatic systems and prevent the loss of metals from the system.

**MAGMATIC ACTIVITY**

In the Carpatho–Pannonian Region (CPR) the most voluminous igneous rocks are calc-alkaline, showing a typical subduction-related geochemical signature (i.e., high LILE/HFSE ratios, negative Nb, Ta and Ti anomalies; lower $^{87}$Sr/$^{86}$Sr and higher $^{143}$Nd/$^{144}$Nd radiogenic isotopic ratios). According to Seghedi and Downes (2011), this suggests their provenance from mantle lithosphere, but as the active subduction period apparently took place in the Paleocene – Early Miocene interval and not in Middle Miocene time, all volcanic products are better considered as post-collision and extensional (Seghedi et al., 1998; Berbeleac, 2003; Harangi, Lenkey, 2007; Seghedi, Downes, 2011). The extension was the main process during which magmas were generated. This mechanism was associated with strike-slip movements and Miocene magmatism in narrow extensional volcano-sedimentary basins. Porphyry copper-gold deposits are hosted by calc-alkaline andesite-porphyry diorite intrusions, Middle Miocene (Sarmatian – Pannonian) in age. Hornblende ± pyroxenes ± biotite quartz andesite (Barza type) and quartz diorite and microdiorites are the most representative host rocks. The Miocene magmas have been very rich in fluids and they had a heterogeneous source at the crust-lithosphere mantle boundary (Seghedi, 2004).
The ages and petrochemical compositions of Neogene volcanic products from SAM are roughly coeval and similar with Tokay – Slanke area and Beregovo – Vihorlat – Oaş – Gutai – Tibles are segment of Carpathians area (Pékay et al., 1995, 2000; Roșu et al., 2004).

The products range from basaltic andesite to dacite–rhyodacite and their subvolcanic correspondents. Neogene volcanic activity is partly coeval with Badenian and Sarmatian molasse deposits. The Neogene magmatic rocks from SAM range in age from 14.7 to 7.4 Ma, except for the 1.5 Ma Uroi trachyandesite (Table 1; Roșu et al., 2004). In general, on the basis of analysis, ages, geochemistry and petrology, the following main distinctive types of volcanic rocks are recognized: 1) Upper Badenian – Lower Sarmatian volcano-sedimentary formation with a large spreading in all volcano-tectonic basins, especially Hâlmagiu – Brad – Săcărâmb and Zarand basins. This formation consists of hornblende andesite, hornblende quartz andesite and dacite pyroclastics (brecias, tuffs), andesitic conglomerates and sand beds intercalated into sedimentary rocks. The thickness of this formation usually ranges between 50–100 m, increasing up to 200 m in the Hârtăgani – Săliște area (Berbeleac, 1975). Curechiu pyroxene–amphibole andesite (14.7 ± 1.7 Ma), Bucium amphibole–pyroxene microdiorite (14.87 ± 0.82 – 14.7 ± 0.8 ), Citera amphibole–pyroxene andesite from Bucium (14.66±1.6 Ma), Cetate dacite (13.5 ± 1.1 Ma), Câinel hornblende–biotite quartz andesite and Tălagiu pyroxene–amphibole andesite (13.4 ± 0.6 Ma) are the main types of rocks generated in this time interval; 2) the period between Lower Sarmatian – Upper Pannonian (12.8 ± 0.6 – 7.4 ± 0.3 Ma) coincides with the maximum intensity of volcanic activity in which great volumes of pyroxene andesite were generated in ZM (13.0 ± 1.7 – 12.43 ± 0.79); Barza hornblende, quartz ± pyroxene ± biotite andesite (12.8 ± 0.6 – 11.99 ± 0.50 Ma), Săcărâmb hornblende quartz andesite ± biotite and pyroxene (12.58 ± 0.5 – 10.35 ± 0.43 Ma) and Citeraș hornblende, biotite ± pyroxene quartz andesite (11.7 ± 0.5 – 11.2 ± 0.9 Ma) being the main types, with a diversity of subtypes. The last volcanic activity took place during the Upper Pannonian in the Rošia Montană – Bucium – Baia de Arieş area where the most representative rocks-types are Rotunda amphibole and pyroxene andesite (9.35 ± 0.5 Ma), Poieniţa amphibole–biotite–quartz andesite (9.31 ± 0.39 Ma), Surligata amphibole–pyroxene andesite (7.06 ± 0.91 Ma) and Detunata basaltic andesite (7.4 ± 0.3Ma). Roughly, from petrology, geochemistry, eruptive style and age, the volcanic products from ZM are essentially correlatable with the Mecsek and Villány Mts. (Hungary) and Oaş Mountains products (Romania).

The architecture of Badenian – Pannonian volcanic structures shows a great diversity of forms (Berbeleac et al., 1995a), such as: small and isolated volcanoes (e.g., Ancii, Bulz, Știrba) to large composite volcanoes with polystadial evolution, stratovolcanoes (e.g., Tălagiu, Cetraș) and ring dikes structures (e.g., Voia, Săcărâmb, Porcurea, Colnic, Musariu; Fig. 4) with small subvolcanic andesite–microdiorites dikes and stocks (e.g., Tălagiu, Săcărâmb, Voia, Cetraș – Măcriș, Bolcana, Musariu, Valea Morii Nouă, Colnic; Fig. 5), explosive volcanoes with vent breccia and diatreme-maarr structures (e.g., Roșia Montană, Bucium Rodu – Frasin, Porcurea) and possible caldera (Tălagiu?, Porcurea). Numerous ring structures and circular swarms of volcanic conduits are usually accompanied by andesite pyroclastics and lava ± epiclastic material.

The Neogene volcanic activity from SAM has been roughly controlled by the tectonic lineaments (in parentheses the interval of volcanic activity): 1) E–W in ZM (13.4 ± 1.2 – 12.43 ± 0.79 Ma); 2) E–W, Brad – Almașul Mare – Zlatna (12.81 ± 1.27 – 11.07 ± 0.63); 3) E–W, Roșia Montană – Roșia Poieni – Baia de Arieș; 4) SW–NE, Deva (12.8 – 11.85 ± 0.46 Ma) – Săcărâmb (11.17 ± 0.48 – 10.89 ± 0.58 Ma); 5) SE–NW, Boteş – Bucium – Baia de Arieş (10.99 ± 0.44 – 7.4 ± 0.3Ma) and, 6) NW–SE, Vârfuri (12.43 ± 0.79) – Brad (12.81 ± 1.27 – 11.07 ± 0.63) – Săcărâmb (10.89 ± 0.58). Along of these lineaments the ages of volcanic rocks in generally seem to decrease from West towards East but the initiation of volcanism appears coeval in MM area.
Fig. 4 – Simplified geological cross-section through Musariu gold deposits (from Berbeleac, 2003). 1, Sarmatian multi-stage subvolcanic intrusions; 2, Andesite-quartz andesite-porphryy diorite (a), Hb ± Px diorite (b); 3, Andesite (Barza type); 4, Upper Jurassic ophiolite; 5, Sarmatian andesitic and quartz andesitic pyroclastics and lava flow; 6, Explosion and tectonic breccia; 7, Potassic alterations; 8, Ophiolite; 9, Phyllic-propylitic (a) and argillic (b) alterations; 10, Alterations; 11, Badenian sedimentary and volcano-sedimentary deposits.
Fig. 5 – Geological cross-section within the Tălagiu area (acc. Berbeleac et al., 1992). 1, lavas and volcanoclastic rocks; 2, hornblende-hypersthene-andesite (a), microdiorite porphyry (b); 3, pyroxene andesite (a), hornblende-hypersthene andesite (b); 4, conglomerate (a), sandstones (b); 5, hornfels; 6, propylitic alteration; 7, boundary between argillic and phyllic alteration; 8, boundary between phyllic and feldspathic alteration; 9, quartz-pyrite ± gold stockwork; 10, mineralized fracture.

3. NEOGENE PORPHYRY COPPER DEPOSITS/PROSPECTS

CHARACTERISTICS OF PORPHYRY DEPOSITS/PROSPECTS

In “Preliminary model of porphyry copper model”, Berger et al. (2008) define a porphyry copper deposit as: 1) One body in which copper-bearing sulfides are situated in a network of fracture-controlled stockwork veinlets and as disseminated grains in the adjacent altered rock matrix; 2) Between alteration and ore mineralization at 1–4 km depth and magma reservoirs emplaced into the shallow crust (6–8+ km), intermediate to silicic in composition are genetically relationship, in magmatic arcs
situated above subduction zones; 3) Intrusive rock complexes that host the deposits are emplaced predominantly as vertical cylindrical stocks and (or) complexes of dikes immediately before porphyry deposit formation; 4) Potassic alteration zone and partial propylitic alteration overlap phyllic-argillic alteration zones and marginal propylitic alteration overlaps or surrounds a potassic alteration assemblage; and 5) Copper may also be introduced during overprinting phyllic-argillic alteration event.

In hypogene porphyry copper deposits, the copper occurs mainly in chalcopyrite, more rarely in bornite and enargite. These minerals occur as disseminations in rock’s matrix and in stockworks of veins and veinlets in the hydrothermally altered rocks of shallow intrusive complexes, often porphyritic, and in adjacent country rocks, frequently hornfels. This model covers all porphyry-style copper deposits and includes copper-molybdenum, copper-molybdenum-gold, and copper-gold subtypes that are sometimes distinguished by economic geologists (for example, Sillitoe, 2000).

The main characteristics of the porphyry copper deposits in SAM include:

- The orebodies are associated with multistage intrusions and/or complex dikes of calc-alkaline andesite-quartz andesite-diorite with porphyritic textures.
- The age of Cu–Au–(Mo) porphyry and Au–Ag–Pb–Zn–(Cu)–(Te) epithermal systems ranges probably between 13–9.3 Ma, corresponding to the Sarmatian–Pannonian interval (Table 1).
- The Cu–Au–(Mo) porphyry deposits usually are hosts of Au–Ag–(Te) and Pb–Zn–(Cu)–Au–Ag deposits/prospects of epigenetic hydrothermal veins, breccia bodies and impregnations.
- The porphyry Cu–Au–(Mo) deposits typically have a core with secondary biotite, orthoclase alteration zone (potassic alteration zone), containing most of the mineralization, and an outer propylitic zone with epidote–chlorite–albite–pyrite mineral alteration.
- The phyllic alteration zone (quartz-sericite) appears locally, along the veins where it partly overprints the potassic and propylitic alteration zones.
- Advanced argillic alteration zone is dominant in the upper part of the central potassic zone. It may be subject to supergene enrichment.
- The highest-grade ore is usually associated with fractures and quartz veins filled by sulfides and iron oxides.

The upper portions of porphyry Cu–Au–(Mo) deposits/prospects can be affected by supergene enrichment. This involves the metals in the upper portion (oxidation zone) being dissolved and carried down to below the water table (cementation zone).

LOCATION OF PORPHYRY DEPOSITS/PROSPECTS

Porphyry deposits occur in close association with small intermediate intrusions emplaced at very shallow depths. The locations of 20 Miocene porphyry epithermal Cu–Au–(Mo) and Au–Ag–Pb–Zn–(Cu)–(Te) epigenetic hydrothermal systems from SAM show a wide scatter (Fig. 1).

The localization of Neogene porphyry epithermal and related epigenetic hydrothermal deposits/prospects is determined by the nature and geometry of pre-extension event rocks (Gow and Walsh, 2005), in this case chiefly the thrust and nappe structures and the crustal faults (Berbelec et al., 2014).

According to Roșu et al. (2004) most magmatic rocks are distributed along two alignments: one, of about 100 km long trending WNW–ESE between Miniș to the west, and Zlatna to the east and another, with ca. 60 km length between Deva to southwest and Baia de Arieș to northeast. According to Ciobanu et al. (2004) and references therein, the majority of 64 ore deposits/prospects from QG occur within three main NW–SE trending volcanic alignments: Zarand–Brad–Săcărâmb, Zlatna–Stânița and Roșia Montană–Bucium. These alignments have been generated as response to the extension of lithosphere along crustal faults. The maximum intensity of magmatic and metallogenetic activity took place at the intersections of W–E and NE–SW with NW–SE crustal fault systems (Berbelec et al., 2010,
The spatial configuration of the 20 porphyry systems is as follows: 2 prospects in the Tâlăgiu area (Central and Northern subvolcanic bodies), one in the Zarand Mountains (Perry et al., 2001, unpublished) and 17 porphyry systems in MM with the following distributions: 5 deposits in Brad (Musariu, Valea Morii, Cireșata)–București–Rovina (Remetea, Kolnic) area, 1 deposit (Bolcana) and 1 prospect (Voia) in the Barbur–Voia area, 7 prospects in the Zlatna–Stânița area (Larga–Horia level 516 m, Trâmpoele, Popa–Stânița, Muncăceasca West, Valea Tisei and Runculețe) and 2 deposits in the Roșia Montană–Bucium–Baia de Arieș area (Bucium Tarnița and Roșia Poieni), and 1 deposit in NE Poiana Ruscă Mountains (Deva).

**FORM OF DEPOSITS**

In SAM, like in other provinces of the world, the porphyry copper–gold deposits are associated usually with stocks emplaced at shallow (1–2 km) crustal levels (Cox, Singer, 1988) with quartz–magnetite–pyrite–chalcopyrite veins and disseminated grains in the rock mass. Usually, magnetite–chlorite ± anhydrite alteration is associated with the main-stage of mineralization and early alteration (potassic). The stocks have small dimensions, displaying circular or ellipsoidal shapes in horizontal sections, with diameters ranging between hundreds of metres up to 1 km (Voia, Bolcana, Valea Morii, Musartu), rarely exceeding 1 km (Tâlăgiu, Roșia Poieni). In vertical plane the bell shape is dominant. A particular shape of overthrust boot characterizes the Voia copper–gold porphyry prospect. The known vertical extension does not exceed 1.5 km. The majority of stocks are multicomponent and widely preserved within coeval volcanic sequences of stratovolcanoes (Voia, Tâlăgiu), which are cross-cut by these intrusions. In some cases the volcanics have been eroded entirely and the stocks are hosted by Cretaceous (Roșia Poieni, Bucium Tarnița, Trâmpoele, Muncăceasca West) or ophiolite (Musariu) basement rocks.

Porphyry systems are spatially and genetically associated with epithermal systems, this being the main support regarding the continuous progression from magmatic to hydrothermal systems. The porphyry mineralization roughly represents a stock (e.g., Roșia Poieni, Bucium Tarnița, Valea Morii, Musariu, Cireșata), dike (Muncăceasca West) or stocks with large lateral extensions in the upper part along the structural discontinuities of the basement (Voia – Fig. 6).

Post-emplacement uplift and erosion of 1–1.5 km has probably destroyed partly or entirely the upper part of these systems which have been formed at depths from 1 to 4 km in the Earth’s crust. In this situation are probably the Roșia Poieni and Valea Morii porphyry Cu–Au deposits, where uplift and the erosion removed part of the ore stock together with the epithermal veins network related to these systems, or part of it, in contrast to other Cu–Au–(Mo) porphyry epithermal deposits and Au–Ag–Pb–Zn–(Cu)–(Te) epithermal systems (e.g., Tâlăgiu, Musariu, Voia, Colnic, Trâmpoele and others; Fig. 5, Table 1), where the uplift and erosion of these systems must have been minimal after the deposits/prospects formed. The preservation of the porphyry deposits may be promoted by buildup of an extensional setting after ore deposition, if major structural disruptions did not occur after ore formation (Cooke et al., 2005).

**ASSOCIATED STRUCTURES AND DEPOSIT TYPES**

A great variety of deposit types are spatially and genetically related to porphyry copper mineralizations from SAM.

The porphyry systems in SAM, as other similar systems from the literature (e.g., Hedenquist et al., 2000) comprise Cu–Au–(Mo) porphyry mineralizations and low-intermediate to high-sulphidation alterations–mineralizations; disseminations and altered subvolcanic stocks; fissuring, veins and breccia bodies with Au–Ag and Te and Au–Ag tellurides, as in the Musariu porphyry system (Berbeleac, David, 1982; Săbău et al., 2013), and/or Au–Ag–Pb–Zn–(Cu) (i.e., Valea Morii, Muncăceasca West, Popa Stânița, Bucium Tarnița) and As–Cu (i.e., Roșia Poieni, Voia–Pârâul lui Avram, Bucium–Corabia) as the most common mineralization types. Skarns with pyrite are known at Voia (Berbeleac, 1998) and Larga–Horia level 516 m (Ciobanu et al., 2004) respectively (Table 1). Gold in varying abundances and economic interest is characteristic for porphyry mineralizations.
Cu–Au porphyry systems usually are superposed by large varieties of mineral assemblages of High (HS), intermediate (IS) and Low sulphidation (LS) epithermal systems. The preservation of one or two of these epithermal systems depends mainly on the intrusion depth, fluids composition and the erosion degree. In favourable situations, all three styles of epithermal systems may occur in deepening subvolcanic bodies, like in the Tâlagiu area (Berbeleac, Andrei, 1989) and Voia (Berbeleac et al., 2012). The Cu–Au porphyry system had a polystage evolution especially remarked by several fissure sets with different directions and mineral assemblages, which reflect a succession of compression and extension events in the time of ore forming. The most expressive aspects regarding to telescoping Cu–Au porphyry systems with epithermal HS, IS and LS occur within the Voia, Musariu, Valea Morii, Muncăceasca Vest and Tâlagiu Neogene structures.

In some districts (for example, Christmas, Arizona, and Battle Mountain, Nevada), more copper is recovered from the host calc-silicate rocks than from the source intrusive rocks. Polymetallic replacement deposits occur in carbonate-bearing units peripheral to porphyry-style mineralization. At Bingham, Utah (Babeck et al., 1995) and Bisbee, Arizona (Bryant, Metz, 1966), polymetallic replacement deposits surround the intrusive complexes with offshoots appearing to radiate outward from the stocks. Vein deposits occur peripheral to many porphyry copper deposits (for example, Bingham, Utah), as well as crosscutting porphyry-style mineralization (for example, Valea Morii, Romania).
It appears obvious that both the epithermal LS Au–Ag–(Te) veins and breccia bodies at Musariu and the Pb–Zn–Au–Ag–(Cu) veins from Valea Morii, Bociana, Voia, Tâlăliugiu, Muncăceasca West (Table 1) are not only spatially, but also genetically connected with porphyry systems. At Voia and Larga–Horia level -516 m, the porphyry system is associated with pyrite–chalcopyrite skarn (Berbeleac, 1998), respectively with Pb–Zn skarn (Ciobanu et al., 2004), and both systems with Pb–Zn–Cu–Au–Ag HS, IS and LS veins (Berbeleac et al., 1984, 1985, 1988). Udubaşa (1982) described at Coasta Mare–Hondol a HS As–Au epithermal system. Porphyry and epithermal systems like Voia occur also in the Tâlăliugiu zone (Berbeleac et al., 1995a, b).

The gold was introduced within porphyry systems with copper, especially during K-feldspar and phyllic alteration (Cioflica et al., 1995). In porphyry ores, the gold contents increase with copper contents (Borcoş, Berbeleac, 1983; Berbeleac et al., 1988, 1995b, 2012b; Halga et al., 2010) and the quartz fissures with pyrite and chalcopyrite are the main carrier for gold which occurs as free micron-sized grains, and within chalcopyrite, both as inclusions invisible (Bociana, Voia, Valea Morii, Roştia Poieni), (Berbeleac et al., 1984, 1988, 2012; Halga et al., 2010), bornite (Deva – Boştinescu, 1984; Mihu, Pintea, 2001) and pyrite (Voia, Berbeleac et al., 1988, 2012b). For instance, at Voia, the free gold has been observed as micronic grains in quartz fissures in the potassic alteration zone. Here, like in other Cu–Au–(Mo) porphyry systems from SAM, the most amount of gold is invisible, and it was introduced together with chalcopyrite generations (tens of g/t), characteristic being the quartz–chalcopyrite–pyrite–magnetite–hematite (specularite) ± anhydrite assemblage (Berbeleac et al., 2012b). Pyrite of this assemblage is relatively poor in gold, the highest contents (tenths of g/t) having been observed within pentagonal dodecahedron pyrite from the central parts of quartz fissures. In porphyry systems from Deva and Bociana (Berbeleac et al., 2000) the free gold (1–25 μ) prevails in bornite–chalcopyrite–magnetite and, respectively, chalcopyrite–pyrite, sporadically in bornite, covellite, sphalerite, galena, molybdenite and unidentified Au and Ag tellurides. The free gold from these assemblages contains (wt %): Fe = 0.1–1.2; S = 0.1–1.5; Hg ≤ 0.2; Bi = 0.067; Ag = 1.3–6.8 and Zn ≤ 0.1. It has high fineness (84.3–90.0 wt %) and represents different generations differentiated through Bi, Cu, Ag and Hg contents. Some minerals associated with free gold show low contents in invisible gold, such as: 0–0.1 in pyrite, chalcopyrite and bornite, 0.14 in covellite, 0.0–0.06 in magnetite, 0.389 in sphalerite and 0.479 in molybdenite.

Low values of Ag (0.5–5 ppm) in known ores of porphyry systems from SAM are in contrast with usually raised values (tens up to rarely thousands ppm) of low-, intermediate- and high sulphidation vein ores.

The Cu–Au–(Mo) porphyry systems from SAM (Tâlăliugiu, Musariu, Muncăceasca West) are accompanied by magmatic-hydrothermal or hydrothermal breccia diatremes and breccia dikes, the latter ones being enriched in gold (e.g., Deva deposit).

Polystage evolution of porphyry and epithermal systems from SAM seems to take place in five main stages, as in Fig. 7: 1) magma intrusion, and crystallization of marginal parts of magmatic chambers, potassic and phyllic alteration; 2) magmatic fluids exsolution, early fissuring and barren quartz fissures forming in the potassic zone with probably extending in the propylitic zone. Homogenization temperatures of fluid inclusions from quartz (q) are: Th = 400–>500 °C and 43 to 60 wt.% NaCl equivalent; 3) further magmatic fluids exsolution and main fissuring, meteoric water influx and appearance of phyllic and argillic alterations: Cu–Au–(Mo) mineralization characterized by a great variety of fissure sequences and disseminations with quartz and sulfides; 4) ascensional migration of the volatile plume along fractures and appearance of hydrothermal alteration and Au and Au–Ag mineralizations. Th = 197–290°C and 0.7–2.4 wt. % NaCl equiv.
From geochemical point of view in argillic alteration, Cu and Au give geochemical anomalies of different intensities, more elevated being those of Pb, Zn, As and Sb and sometimes, Hg, as Tălagiu (Perry et al., 2001). According to Sillitoe (1992) the argillic alteration could be considered as the result of late hydrothermal activity of porphyry systems in decline, and that interface between this alteration type and other alteration types could represent the transition between epithermal and hydrothermal regimes.

LITHOLOGICAL ASSOCIATION

The porphyry Cu–Au deposits are believed to be independent of the composition and thickness of the underlying crust, which can be primitive, oceanic to evolved cratonic in character. The relatively reduced crustal units may buffer the redox state of magmas which ascend through them, the drop in oxidation state being especially favorable for generation of gold deposits in general, and gold-rich porphyry copper, in special (e.g., Keith, Swan, 1987). The ideas about the correlation between molybdenum-rich deposit and continental settings and between gold-rich and oceanic settings (e.g., Hollister, 1975), are discredited by the discovery the Marte and Lobo porphyry gold deposits from northern Chile, which are located in a thick Andean crust (Vila, Silitoe, 1991).

The stocks usually are composite including at least 3–4 rock types. The main intrusion in the upper part is andesite, evolving towards depth to microdiorite; frequently in the central zone, the main stocks contain younger andesite and microdiorite small intrusions (Ionescu, 1974; Borcoș, Berbeleac, 1983; Boștnescu, 1984; Berbeleac et al., 1985, 1992, 1995, 2012, 2015; Kouzmanov et al., 2003, Ruff et al., 2012; Kun et al., 2012). These later intrusions (dikes) are compositionally roughly similar with the main andesite and microdiorite, the difference consisting in the fine-cryptocrystalline ground mass. These later dikes cut early stock fissuring and are fresh or less altered and mineralized.
Usually, the main andesitic-microdiorite porphyry stocks frequently contain in both their central parts and/or along their margins small younger dikes and veins, in general with similar compositions (Borcoș, Berbeleac, 1983; Boştinescu, 1984; Berbeleac et al., 1982, 1985, 1995a; Cioflica et al., 1995). These younger small intrusions are sometimes hardly noticeable, contrasting usually by lesser alteration, dark-grey colour and fine cryptocrystalline textures.

Small values of K₂O/SiO₂ in Cu–Au–(Mo) porphyry mineralized rocks show their affiliation to type I (Ishihara, 1981) and the magnetite series: calc–alkaline diorite, quartz diorite and granodiorite. This suite and type of calc–alkaline intrusive rocks are favourable for forming porphyry copper–gold rich deposits, the magma oxidation driving to gold concentration in fluids (Leveille et al., 1988; Candela, 1989) which may be conveyed to the adjacent rock matrix. According to Candela (1989), owing to gold accumulation in the stage of magnetite crystallization type I and related calc–alkaline intrusive rock suites are distinctly favorable for generation of porphyry Cu mineralizations rich in gold; magma oxidation processes are also important in forming these deposits. The Cu–Au–(Mo) mineralized porphyry rocks from SAM are characterized by great variations in the Al saturation index (Al₂O₃ / K₂O + Na₂O + CaO expressed in mols), that ranges between 0.1–4, usually 0.85–1.40, indicating the metaluminous to dominantly peraluminous character of magmas. Note that the values of this index are strongly variable, partly caused by undetected alteration, introducing a sampling bias. Of the total number of 77 samples, with two exceptions (Tălagiu = 30, Voia = 24), the data for individual structures are too few to be considered representative (Bucium Tarnița = 3, Deva = 3, Valea Morii = 4, Musariu = 11, Larga = 2), and require caution in interpretation.

**TYPES OF NEogene HYDROTHERMAL ALTERATION AND ASSOCIATED MINERALIZATION**

Five main hydrothermal alteration types accompany Cu–Au–(Mo) and Au–Cu–(Mo) porphyry mineralization from SAM: potassium–silicate (potassic), sericitic (phylllic), intermediary argillic, propylitic and advanced argillic. The Cu–Au–(Mo) deposits and prospects comprise in different proportions all these types of alteration; the sericitic alteration appears occasionally. Alteration has produced concentrically zoned patterns from central potassic (K–feldspar–biotite ± quartz ± magnetite) core, out to extremity propylitic (chlorite–epidote–calcite ± illite–albite–pyrite) assemblages. In the upper part dominant are intermediate argillic alteration (chlorite–illite ± pyrite) assemblages, which overprinted part of the potassic zone, being synchronous with phyllitic alteration assemblages (quartz– muscovite–illite ± pyrite).

Advanced argillic assemblage, indicated by a suite of acidic clay minerals that include kaolinite, dickite, pyrophyllite and smectite, additionally gypsum, anhydrite, alunite, pyrite and marcasite. Argillic alteration grades to a propylitic zone further away from the veins.

**POTASSIC ALTERATION-MINERALIZATION**

This alteration type is characterized by the following mineral assemblage: biotite, k–feldspar, quartz, anhydrite, magnetite, hematite, pyrite, chalcopyrite ± actinolite, apatite, epidote, albite and gold. Quartz is omnipresent. It invades the rock mass, fissure systems and veins of anhydrite and gypsum in mineral assemblages from Voia, Bolcana, Tălagiu and Trâmpoiele porphyry systems (Berbeleac et al., 1982, 1985, 2012a, b; Ciobanu et al., 2004). Among sulfides, pyrite is dominant. It is followed by chalcopyrite, bornite, chalcocite, gold and covellite, important in the Deva deposit (Ianovici et al., 1977; Boştinescu, 1984; Milu, Pintea, 2001; Ivişcanu, Roşu, 2003). Pyrite is less important in Roşia Poieni, Deva and Bolcana deposits and, contrary, it is a dominant ore mineral in Musariu, Muncăceasca West, Voia, Tălagiu and other deposits and prospects. Pyrrhotite is dominant in Musariu (below 490 m level), Runculeţe and Valea Tisei prospects. This distribution between Fe sulfides and those of Fe and Cu is expressed
in the ratio pyrite/chalcopyrite + bornite which varies in large limits among particular deposits or prospects (Deva = 0.1–0.3 and 0.5–10 in the rest of deposits and prospects).

Magnetite is frequent in all porphyry systems known. It appears disseminated and partially substituted by hematite in the rock mass and along fissure systems. Frequently it is associated with chlorite, K–Na feldspars, anhydrite and quartz and sporadically pyrite and chalcopyrite. In the Voia porphyry system enrichments in magnetite and hematite (7–10%) appear locally, reminding an iron porphyry system. Rutile is recognized as a common mineral in Neogene porphyry systems. It partially substitutes amphiboles and participates together with other minerals in fissure filling. Molybdenite appears sporadically and locally as films without gangue minerals.

Potassic alteration zones from Cu–Au–(Mo) porphyry mineralisation known in SAM were the result of multiple individual episodes during the hydrothermal and also probably magmatic stages, manifested through a large variety of minerals occurring both in the rock mass and along fissure systems. All these features frequently appear in those porphyry systems which were deeply eroded (Roșia Poieni, Bucium Tarnița – Ionescu, 1974) or the deeper levels have been opened by drillings or mining works, such as Musariu, Muncăceasca West, Voia, Tălagiu and others. In these situations, and especially when the early assemblage (quartz – biotite – K–Na feldspar) prevails (Bucium Tarnița, Roșia Poieni), lower metal contents (Cu, Fe, Au) are conspicuous. Sillitoe (1992) explains the metal deficit of early alteration stages through high fluid temperature and correlated increased stability of metal chlorine complexes prevailing over sulfides, and system enrichment in SO$_4^-$ minerals. In contrast, the subsequent depositions of the system as quartz – K–Na feldspar accompanied by chlorite, amphibole ± anhydrite shows increased metals content and ore formation, especially of Cu (> 0.2%) and Au (>0. 2g/t).

**Propylitic Alteration–Mineralization**

Propylitic alteration and related mineralizations are situated outwards from the potassic zone. In contrast with this, it affected alike the rocks of stock in their totality and the host formations, namely: Paleozoic metamorphic basement (Deva, Roșia Poieni, Bucium Tarnița), Jurassic ophiolites (Bolcana, Voia, Musariu, Valea Morii, Cireșata, Colnic, Rovina, Valea Tisei, Muncăceasca West and Trâmpoiele), as well as sedimentary rocks of various ages: Jurassic – Cretaceous (Voia), Cretaceous (Deva, Colnic, Remetea, Roșia Poieni and others) and Miocene (Voia, Valea Morii, Musariu, Larga), including the hornfels formed on these rocks as in the Voia prospect (Berbeleac et al., 2010) and Musariu and Muncăceasca West deposits. The mineralized structures consist of Cu–Au porphyry stocks, veins and breccias with Au–Ag (±Te) (e.g., Musariu, Colnic) and/or Pb–Zn ± Au–Ag–Cu (Valea Morii Nouă, Popa–Stânija, Muncăceasca Vest, Bolcana). At Voia pyrite ± gold skarns (Berbeleac, 1998) and Pb–Zn skarns at Larga, Horia level -516 m (Ciobanu et al., 2004) also host porphyry Cu–Au–(Mo) systems.

The characteristic mineral assemblage contains: chlorite, calcite, epidote, albite, pyrite, local actinolite, anhydrite, clay minerals, chalcopyrite and magnetite. Because this alteration type interpenetrates with the others alteration types, especially in the contact zones, partial chloritized biotite may be present, besides K–feldspar, sericite, quartz, clay minerals, gold, bornite, hematite and other minerals. In the propylitic zone the intensity of fissuring and mineralization decrease drastically so that towards its exterior metallic minerals usually are represented only by pyrite.

**Intermediate Argillitic Alteration–Mineralization**

Situated in upper part of stocks and partially overlapping K–feldspar, sericitic and propylitic alteration, this type of alteration and mineralization is distinguished by clay minerals (sericite, smectite, illite, kaolinite and dickite) and gypsum together with characteristic minerals of the two mentioned alteration types. Although present in near all Neogene porphyry systems from SAM, this alteration type is difficult to be separated and integrated in zonalities. However, it was separated in upper part of porphyry systems, in peripheric position in both vertical
and horizontal plane, around the advanced argillic alteration as at Voia (Berbeleac et al., 1985) and Tâlăgii (Berbeleac et al., 1992) porphyry systems. The fissure systems characteristic to porphyry mineralisation were well preserved.

Among metallic minerals in the intermediate argillic alteration pyrite prevails, chalcopyrite is less present, while magnetite is martitized or is absent being replaced by hematite. Rutile is present in minor amounts. Quantitatively Mo records no change, Cu and Au decrease and Pb and Zn show slight enrichments.

**SERICITIC ALTERATION–MINERALISATION**

Though has been recognised in all Cu–Au–(Mo) porphyry mineralisations, this type of alteration, as in the case of intermediate argillic alteration, is not well developed with exception of the Musariu (Boroş, Berbeleac, 1983) and Roşia Poieni (Ionescu, 1974; Ionescu et al., 1975) deposits. It appears as white-greenish zones, frequently isolated, situated inside and at the periphery of the potassic zone, partially affecting also the propylitic zone.

Structural control is evident; the harder rocks, with frequently quartz fissures, anhydrite, sulfides with white or white-greenish color, represent sericitic areas. The sericitic zone is distinguished by quartz–sericite–pyrite (5–10%). Other minerals present are chlorite, anhydrite (gypsum), clay minerals, chalcopyrite, bornite, Kfeldspar etc. The contents of Cu, Au, Pb and Zn show large variations, still above those recorded in the potassic zone.

**ADVANCED ARGILlic ALTERATION–MINERALIZATION**

This alteration type is known in all porphyry stocks from SAM; at Roşia Poieni and Bucium Târnăţa, where the erosion is more important, it covers a small area. It is widespread especially in the upper parts of less eroded porphyry systems built up in Mesozoic and Miocene volcanic and sedimentary rocks (i.e., Voia, Musariu, Muncăceasca West, Trâmpoele, Tâlăgii – Fig. 5). The characteristic minerals are: kaolinite, smectite (montmorillonite), dickite, pyrophyllite, alunite, diaspore, quartz-calcedony, gypsum, barite, pyrite, marcasite, base metal sulfides, gold, tellurides, enargite, fataminitine, and molybdenite. Argillic alteration represents the halo with pyrite and marcasite of Voia–Pârâul lui Avram (Soconeșcu et al., 1963; Udubușa et al., 1982), Dealul Talpelor–Ciresata (Ruff et al., 2012) and Bratosin–Tâlăgii Valley (Berbeleac et al., 1982) porphyry systems. These are the largest argillic halo with pyrite and marcasite in SAM.

**FLUID INCLUSIONS DATA**

Fluid inclusions and isotopic studies of Cu–Au–(Mo) porphyry deposits from diverse metallogenetic belts (Eastoe, 1982; Cox, 1985; Trudel, Bloom, 1987; Bowman et al., 1987; Sillitoe, 1992; Quan et al., 1987; Nedelcu et al., 1999) as well as SAM (Pintea, 1993a, b, 1997, 2012) shown that Cu and Au have been transported in the potassic alteration zones as chlorine complexes in high temperature magmatic–hydrothermal brines (T = 350 up to 750°C). Brine was the main fluid phase in porphyry copper ± skarn deposits and occurrences in the Alpine metallogenetic belt (Pintea, 1993a, 2002; Heinrich et al., 2005; Pintea, 2012). Hydrosilicate glass inclusions (T_h = 940–1170°C) and aqueous pairs (H_2O–rich vapor ± CO_2 and H_2O–rich liquid) and also, immiscible Fe–(S–O) inclusions generally originated in metasomatic and magmatic processes (Pintea, 2010, 2012, 2014). Conditions derived for the saline fluid phase have been the following: T = 420–1300°C, P = 0.1–12 kb and salinity = 31 – 89 wt% NaCl equiv. (Pintea, 2009; 2012). The fluid and melt inclusion study of Alpine porphyry copper systems from SAM (Pintea, 2012) shows that magmatic and metasomatic processes are responsible for potassic, phyllic and propylitic assemblages and remelted sulfides. According to Sillitoe (1992) brines are immiscible aqueous fluids at high temperatures, and Cl, S and probable Cu and Au in potassic zones are supplied by the dehydration of the oceanic crust from below volcano–plutonic arcs. These brines initially confined in magmatic chambers, due to decompression
become free and migrate above into the porphyry stock; ore deposition takes place in a transition zone with litho–hydrostatic regime in which the mechanical energy achieved during repeated events of secondary boiling produced the rocks fissuring and brecciation accompanied by dilution, cooling and destabilizing of the chlorine complexes from brines. All these processes lead to copper, gold and other metals deposition especially within fissure systems. Cooling and progressive mixture of brines with meteoric water or the water formed in the host rocks induced propylitic alteration, poor in metals or barren.

Brines ascending towards the upper part of porphyry systems (stocks) were accompanied by aqueous solution immiscibility yielding less dense acid volatiles eventually mixed with meteoric water. In these conditions takes place the argillic alteration where transport and deposition of metals (Cu, Au, As, Hg) occurs from fluids and from volatile chlorine complexes (Cline, Bodnar, 1991). As regards the phyllic alteration, this can result from condensation of magmatic volatiles in meteoric water (Sheppard et al., 1971). Penetration of meteoric water, relatively cold, in incompletely cooled mineralized stocks can be responsible for forming phreato–magmatic explosion (Sillitoe, 1992) as diatremes and breccia dikes such as Roșia Montană, Porcurea–Coranda, Musariu, Bucium Rodu–Frasin and others.

In SAM, the EDAX quantitative analysis on mineral inclusion (daughter phase) from pyrites and sphalerites of some porphyry deposits point out different chemical compositions (Nedelcu et al., 1999), such as:

A. 1) K–Fe–Cl, Cu–Fe–Cu–Cl and K–Cl chlorides in pyrites of Cu–Au–(Mo) Valea Morii porphyry deposit;

2) chlorides within pyrites of some auriferous and base metals sulfides–gold associated with Cu–Au porphyry deposits: Cu–Fe–Cu–Cl (Valea Morii), K–Cu and Cu–Cl (Musariu), and K–Fe–Cl (Carpen);

3) chlorides in pyrites of some base metals sulfides–gold veins associated with Cu–Au porphyry deposits: K–Fe–Cl (Valea Morii, Voia, Haneș, Larga) and

4) chlorides in pyrites of some gold breccia bodies without connection with Cu–Au porphyry mineralization: K–Cl and K–Fe–Cl (Baia de Arieș);

B. 1) chlorides in sphalerites of some auriferous veins associated with Cu–Au porphyry deposits: K–Zn–Cl (Musariu) and K–Zn–Au–Cl (Carpen).

Fluids phase evolution associated to alteration–mineralization processes from Talăgiu achieved probably in two principal stages, such as: 1) thermobaric regime Th ≥ 700–750°C, 200–250 bar, with hydrosaline melt (Na, Cl, KCl, CaSO₄, Fe₂O₃) and vapors (H₂O+CO₂+H₂S) (immiscibility), for the quartz pyrite I paragenesis and 2) anhydrite–pyrite II, the thermal regime dropping to 450–200°C with aqueous solutions (SO₄²⁻, Cl, Na⁺, K⁺, Ca²⁺) and H₂O+CO₂+H₂S vapors, followed by quartz II – pyrite II ± calcite during évaporation at T<200°C, further drops in temperature triggering vapors rich in H₂O, SO₄²⁻, HCO₃⁻ and deposition of cryptocrystalline silica + gypsum.

GRADE AND TONNAGE DATA

The porphyry copper deposits/prospects from SAM, as other similar ones from the world, are characterized by variation and concentration of accompanying commodities, especially molybdenum and gold metals in individual deposits/prospects. From this perspective, the resources are subdivided into three subclasses: copper, copper–molybdenum, and copper–gold, according to their grade and tonnage data (Cox, Singer, 1986; Berger et al., 2008). Cox and Singer (1988), based on the gold/molybdenum ratio, divided the first subclass, copper, in three subtypes, as follows: copper–gold, copper–gold–molybdenum, and copper–molybdenum, the subtype boundaries being: ≥30 at porphyry copper–gold deposits; 3–30 copper–gold–molybdenum deposits and ≤3 for gold–molybdenum deposits. The previous studies have suggested linkages between the by-product content of porphyry copper deposits and different geological attributes. According to Kesler (1973) there are two types of deposits, copper–molybdenum and copper–gold, the latter
being smaller than the former ones. This author explains the differences between the primary compositions of mineralizing systems through responses to some distinct geologic features such as the level of granitoid emplacement, permeability and/or wall-rock chemistry. Sillitoe (1979), defining gold-rich deposits as averaging more than 0.4 gram gold per ton, and concluded (Sillitoe, 1993) that increased magnetite content and calc–silicate alteration minerals, including amphibole, pyroxene, and(or) garnet, tend to occur in gold-rich varieties. In addition, he remarks that both copper–molybdenum and copper–gold deposits relate to calc–alkaline intrusive complexes, but only gold-rich deposits occur in alkaline intrusive complexes.

Grade and tonnage data for the porphyry copper deposits in SAM, based on contained copper and gold ore are listed in Table 1. These data came from own studies, above mentioned, compiled from other sources as The Geological Institute of Romania, the archive of the S.C. Prospețiuni S.A. and MINEXFOR, Deva, as unpublished geological reports cited in published papers (Borcoș, Berbeleac, 1983; Borcoș et al., 1977, 1998; Berbeleac et al., 1985, 1988, 2010, 2012; Halga et al., 2004; Ciobanu et al., 2004; Drew, 2005; Kouzmanov et al., 2005; Popescu, Neacșu, 2005, 2007, 2012; Ruff et al., 2012; Kun et al., 2012) and others.

In the matter of copper porphyry systems classification Clark (1995) proposed the following size subdivisions: < 0.1 Mt contained copper (small); 0.1 to 0.3162 Mt (moderate); 0.3162 to 1.0 Mt (large); 1.0 to 3.162 Mt (very large); 3.162 to 10 Mt (giant); 10 to 31.62 Mt (super giant) and > 31.62 Mt (the largest). Using this classification most of the Miocene copper porphyry deposits from SAM can be considered as small (< 0.1 Mt Cu), with the exception of Valea Morii which has 0.26 % Cu and 0.49 g/t Au (André-Mayer et al., 2001) and Roșia Poieni which comprises 431 Mt with 0.36% Cu and 0.29 g/t Au.

Clark (1995) makes the remark that there are no systematic qualitative differences between giant and small porphyry deposits. However, giant porphyry deposits tend to cluster within mineral provinces. This means that geodynamic setting and crustal architecture played an important role in localizing giant porphyry deposits. This is easy to see the locations of 25 largest porphyry copper deposits which are focused especially in Central and South America and SW Pacific, whereas North America and Eurasia only a few super giant copper porphyry deposits are known.

CONCLUSIONS

A number of 20 porphyry Cu–Au deposits and prospects, generally small-sized, have been identified so far in a relatively restricted area in the SAM, corresponding to the Golden Quadrilateral. They are associated to a complex of volcanics and shallow-level intrusions emplaced during a Tertiary (14.7–7.4) magmatic event.

At variance with the classical porphyry model of Sillitoe (1998), the magmatic complex was emplaced in an extensional tectonic setting, coevally with North–South trending wrench faults and their secondary structures. The extensional regime is supported by deposition of molasse formations filling intramountaineous pull-apart basins starting in the Paleogene, associated to volcano-sedimentary sequences (pyroclastics, tuffs) intercalated in the detritic deposits with marine–lacustrine facies. The tertiary magmatism evolves from dacitic (Roșia Montană Dacite) to andesitic compositions represented by amphibole and quartz andesite locally enriched in biotite or pyroxene (Barza, Săcărâmb, Porcurea types). The volcanic rocks are accompanied by widespread subvolcanic equivalents forming shallow intrusions which consist of porphyry quartz microdiorite, porphyry diorite and hornblende andesite.

In contrast with the compressional porphyry formation model, which relies on overpressure of volatile-rich magmas achieved in a compressional setting, triggering brittle failure of the overriding crust and subsequent decompression, hydrothermal alteration and ore deposition, the extensional setting enables magma emplacement and fast volatile discharge along the pathways created during deep-reaching extensional faulting. Magmatic complexes and associated alteration haloes emplaced in an extensional setting are, as
a consequence of these differences, characterized by smaller size and higher scatter of the magma chambers, as well as a more intense structural control exerted by the basement.

The shape of the shallow level intrusions in SAM consists dominantly of stocks and subordinately ring dikes, the stock tendency to group in circular clusters in individual magmatic centres. The flat-lying tabular structure of the basement and its lithological (and mechanical) diversity often induces characteristic lateral extensions of the main subvolcanic conduits like sills, apophyses, and irregular bodies of both the intrusions and accompanying alteration zones.

Five main hydrothermal alteration types accompany Cu–Au–(Mo) and Au–Cu–(Mo) porphyry mineralization in SAM: potassium silicate (potassic), sericitic (phylllic), intermediate argillic, propylitic and advanced argillic. The Cu–Au–(Mo) deposits and prospects comprise in different proportions all these types of alteration; the sericitic alteration appears occasionally. Alteration has produced concentrically zoned patterns, from a central potassic (K-feldspar - biotite ± quartz ± magnetite) core to propylitic (chlorite–epidote–calcite ± illite–albite–pyrite) assemblages outwards. Intermediate argillic alteration (chlorite– illite ± pyrite) assemblages are dominant in the upper part of the structures, overprinting also part of the potassic zone, and being synchronous with the phyllic alteration assemblages (quartz–muscovite–illite ± pyrite). The mineralization is of disseminated type (veinlets, impregnations, breccias and networks) and accompanies hydrothermal alteration zones.

The porphyry Cu–Au–(Mo) and partly Au–Cu–(Mo) mineralization is located in the more deeply eroded areas of SAM, consists of several scattered small to intermediate porphyry structures, associated with epithermal veins which cross-cut and cap the porphyry alteration structures or are hosted inside the areas outlined by the circular stock clusters.

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