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

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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 diseminations 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 Cireşata 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).

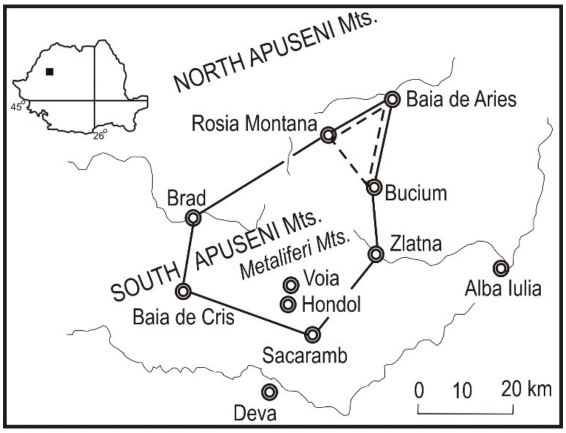

Fig. 1 – The position of the Golden Quadrilateral (GQ) within Metaliferi Mountains.
Thick black line – GQ, Dashed line – Roşia Montană–Bucium–Baia de Arieş District.

Table 1

Summary of main features of Neogene porphyry Cu–Au (Mo) deposits and prospects from South Apuseni Mountains.

Data from: 1 – Berbeleac & Andrei (1989); 2 – Berbeleac *et al.* (1995a); 3 – Perry *et al.* (2001); 4 – Boştinescu (1984); 5 – Berbeleac (1980); 6 – Borcoş & Berbeleac (1983); 7 – Nedelcu *et al.* (2001); 8 – André-Mayer *et al.* (2001); 9 – Kouzmanov *et al.* (2003); 10 – Kun *et al.* (2012); 11 – Ruff *et al.* (2012); 12 – Halga *et al.* (2010); 13 – Milu & Pintea (2001); 14 – Berbeleac *et al.* (1982); 15 – Berbeleac *et al.* (2015); 16 – Berbeleac *et al.* (2014); 17 – Ciobanu *et al.* (2004); 18 – Popa *et al.* (1998); 19 – Ghiţulescu & Socolescu (1941); 20 – Cook & Ciobanu (2004); 21 – Iatan (2009); 22 – Ivăşcanu & Roşu (2001); 23 – Iatan & Berbeleac (2018); 24 – Milu *et al.* (2004).

Area Deposit (D) / Prospect (P)	**Neogene pre-volcanism formations**	**Age (My) Neogene volcanics**			**Alteration type**	**Mineralization**			**Source**
		Pre-ore	Syn-ore	Post-ore		Description	Main/ minor min.	Mineral assemblage	
Zarand Mountains									
South Tălagiu P. (deep)	K_2 flysch; Pg molasse; J ophiolites and island arc volcanic; Pre-Mz metamorphites	Bd-Sm volc.-sed. Fm; hb α, px α, hb-px α	Sm; hb±px α, hb mδp	Sm-Pn (?); px α	K-fds, Pr, Ad, Im ar.	HS, IS, LS 1. Cu-Au porphyry stockwork / oval / 2000 / 0.600m / >110m / 0.1-0.5 %Cu; 0.1- 0.57 g/Au 2. Au-Ag, Au-Ag-Pb-Zn-(Cu), Pb-Zn-(Au-Ag) epithermal veins and breccia bodies	py, mt, cp	k-fds ± mt ± qtz (± bt ± ap); qtz ± mt ± py ± cp ± bt ± k-fds; chl + anh+ py + cp ± bt ± mt; chl + ill + ep+ ep + py; qtz-py ± cp ± anh; anh + py + cp; alu + clm + py ± mc	1, 2, 3
North Tălagiu P. (deep)	K_2 flysch; Pre-Mz metamorphites	Bd-Sm; hb α, px α, hb-px α	Sm; hb±px α, hb mδp	Sm-Pn (?); px α	Pr, Ad, Ar, Im ar.	1. Pyrite crack breccia 2. Epithermal pyrite veins	py	clm - py ± mc qtz - bt - py (hornfels)	3
Metaliferi Mountains									
Musariu P. (deep)	Pg molasse; J ophiolites and rocks of island volcanic arc; Pre-Mz metamorphites	Bd-Sm volc.-sed. Fm; hb α, hb-qtz α as pyroclastics, lavas and intrusion.	Sm; hb ± px ± bt α, qtz α, hb-qtz mδp (older diorite) as intr.	Sm-Pn; hb ± px α and mδp (younger diorite) as small intr.	K-fds, Pr, Ser, Ad, Ar, Im ar.	HS, IS, LS 1. Cu-Au porphyry stockwork / oval /~ 600 / 400m / 1500m / Cu% g/t Au 2. Au; Au-As; Au-Te; Au -Ag-(Pb-Zn-Cu), Pb-Zn-(Au-Ag) epithermal veins and lesser breccia bodies	py, po, cp, mt, he, ru, asp, mo, sph, ga	qtz - mt; qtz - py - cp - mt; qtz - py - cp; cp; k-fds + qtz ± bt ± anh ± py; qtz + cb + py + cp; chl + anh + py + cp ± bt ± mt; chl + ill + ep + ep + py; qtz - py ± cp ± anh; anh + py + cp; qtz - clm - py ± bms; qtz - mt - he; chl - cb - ill - po	4, 5
Valea Morii D.	Pg molasse J ophiolites and rocks of island volcanic arc; Pre-Mz metamorphites	Bd-Sm volc.-sed. Fm; hb α, hb-qtz α as pyroclastics, lavas and intrusions.	Sm-Pn; hb±px α and mδp (younger diorite) as small intr.	Sm-Pn; hb±px α and mδp (younger diorite), as small intr.	K-fds, Pr, Ser, Ad, Ar, Im ar.	HS, IS, LS 1. Cu-Au porphyry stockwork / oval / 60 / 400m / 1500m / 0 .20% Cu, 0.87 g/t Au 2. Au; Au-Ag-(Pb-Zn-Cu), Pb-Zn-(Au-Ag) epithermal veins and breccia bodies	py, po, cp, mt, ru, asp	qtz - mt; qtz – mt – py - cp; qtz – y – cp; cp; k-fds + qtz ± bt ± anh ± py; qtz + cb + py + cp; chl + anh + py + cp ± bt ± mt; chl + alb - ill + ep + ep + py; qtz -py ± cp ± anh; anh + py + cp; qtz – clm – py ± bms; qtz – mt – he; chl – cb – ill – po	6, 7, 8, 9

Table 1 (continued)

Cireşata (deep)	J ophiolites and J_3- K_1 island arc volcanics (basalts, andesites, diorites)	hb-qtz α	hb±px andesite and porphyry diorite (younger diorite)	unknown	LS K-fds, Pr, Ser, Ad, Ar, Im ar.	1. Au-Cu stockwork / cylindrical / 350 / 400m / 65 mil. t (cut- off -1.0g/t Au measured and equivalent, measured + indicated 65 Million t, at 1.01g/t Au and 0.18 % Cu. 2. Au; Au-Ag-Pb-Zn-(Cu)	qtz, chl, mt, py, cp	bt - K-fds - mt; qtx - chl - mt - py - cp; bt- qtz - K-fds - mt - py-cp; ser - py; cb - kol; ser - qtz ± clm - py	10, 11
Colnic	K_1 flysch; J ophiolites; Metamorphites	hb α, hb-px α = Porphyry	Fds-hb-δp = Colic Porphyry	unknown	K-fds, Pr, Ser, Ad, Ar, Im ar.	Cu-Au stockwork py ± cp / cylindrical / ~ 600 / ~400m/ 0.3-1. 3g/t Au, 0.05-0.18 % Cu		bt- qtz - K-fds – mt – py - cp; bt - qtz ± K-fds – py - po - mo	10
Rovina – Remetea	K_1 flysch; J ophiolites; Metamorphites	hb α, hb-px α	Fds-hb-δp “Porph C” and “Porph B”	Phreato-magm. “Glam Breccia”	K-fds, Pr, Ser, Ad, Ar, Im ar.	Cu-Au stockwork py ± cp / cylindrical / ~ 600 / ~ 400m/ 0.3-1. 3g/t Au, 0.05-0.18 % Cu /~ 350m / 600m/ 450-550 m below the surface/ 0.1 - 1.0 g/t Au, 0.05-0.70% Cu.	qtz, , mt, py, po , cp	bt - qtz - K-fds; mt - chl - ep - K-fds ± qtz ± anh ± cb	13, 14, 15
Bolcana	Mc sediments; Pg molasse; K_1 rhyolites; J ophiolites and J_3 -K_1 island arc volcanics (basalts, andesites, diorites); Metamorphites	Sm; hb α, hb-px α breccia	hbα, mδp	hb-qtz α	K-fds, Pr, Phy, Ar.	1. Cu-Au stockwork py ± cp / elliptical (350m / 200m), 0.24-0.43 % Cu, between +600-200m/ ~ 2 Million t, measured + indicated / ~ maximum extension 750 m / 440 m, explored to 1300 m 2. Au and Au-Ag- bms ± teluride epithermal veins	py, cp, mt / bo, he, mo	Bt - K-fds; chl – anhy - ac - alb - ser; ill – phgit - ill - sec. mixed- layer minerals - qtz; ka - sme - mixed layer minerals - cb; chl - ep -ac - sr - cb	13, 14, 15
South Voia (deep)	Sm-Bn sedi., volcano-sed. and volcanic rocks; Pg molasses; J ophiolites and J_3 -K_1 island arc volcanics; Metamorphites	Bd-Sm volcano -sed. Fm; hb α, hb-bi α, hybrid rocks	hb-bi ± px –q α, mδp, hb-bt px- qtz α	hb α, hb α ± px	K-fds, Pr, Phy, Ad, Ar, Im ar	HS, IS, LS 1. Cu-Au stockwork py, cp, mt / elliptical (~800m / ~200m) / 0.315% Cu, 0.2612 g/t Au (drill 19, m. 750-1190), <0.1-0.6% Cu, ~0.6g/t Au (drill 17m 100-1000) / ~ 1200m / maximum extension 1200 m /150-200 m, explored to 1300 m 2. Au and Au-Ag- bms epithermal veins	py, cp, mt, ru / cv, cub, bo, mo	qtz -K-fds – bt - alb - anhy; anhy - py; gs - py - anhy ± mt; qtz – cb - py – bms -Au ± anhy; qtz - aby – mt –he – py - cp; anhy – mt - py ± cp; kao – ill – cal - qtz - cal - gy ± anhy - py; k-fds - alb - bt - mt - he - py - cp; chl - ill - clm - ep - anhy - py ± bms ± mo; qtz - alu - clm ± py ± dia; chl - anhy – mt - cp - py.	11, 12

Table 1 (continued)

North Voia (deep)	Sm-Bn sed., volcano-sed. and volcanic rocks; Pg molasses; J ophiolites	Bd-Sm vol.cano -sed. Fm; hb α, hb-bi α, hybrid rocks	hb-bi ± px –q α, mδp, hb-bt px- qtz α	hb α, hb α ± px	K-fds, Pr, Phy, Ad, Ar, Im ar	No data	py, ± cp	clm - py ± qtz ± mc ± anhy; ill - qtz - py; -cal - gy ± anhy - py	
Runculeţi	K_2 sed.; J ophiolites and J_3 -K_1 island; Metamorphites	K_2 sed.;	unknown	unknown	Im ar.	Po ± Cu ± Au-Ag-bms veins and breccias	po	clm - po - py	
Valea Tisei	K_1 flysch; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	hb α, hb-px α, hb-bi α, breccia	hb α	unknown	IS, LS K-fds, Pr, Ser, Ad, Ar, Im ar	1. Cu-Au stockwork 2. Au-Ag ± bms	po, py, clm	clm - po ± cp ± py ± mc	
Măgura Poienii	K_1 flysch; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	hb α	hb α	unknown	Pr, Ser	1. -? 2. qtz-Au veins	py	chl - alb - ep – clm - cb - py	
Borzeşti-Mormântul	K_2 sed.; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	Sm; hb α pyroclastics and lavas	hb α + mδp ?	unknown	Pr, Ser, Ad, Ar, Im ar	1. -? 2. Qtz-clm-Au; clm-Au-Ag-Pb-Zn epithermal veins	py, po, Au	chl - alb - ep – clm - cb - py	
Măgura Sărunii	K_2 sed.; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	Sm; hb α pyroclastics and lavas	hb α + mδp ?	unknown	Pr, Ser, Ad, Ar, Im ar	Probable Cu-Au porphyry structure			
South Dealul Cutii – Dealul Ludului	K_2 sed.; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	high magnetic anomaly	unknown	unknown	unknown	Probable Cu-Au porphyry structure			
Popa Stănija – Olga	K_2 sed.; J ophiolites and J_3 -K_1 island volcanic arc; Metamorphites	hb α	hb α, p δp	unknown	LS K-fds, Pr, Ser, Ad, Ar, Im ar				17, 20
North Baba – Băbuţa	Pg molasse (Faţa Băii formation); J ophiolites; Metamorphites	hb α	unknown	unknown	Pr, Ser, Ad, Ar				

Table 1 (continued)

Trâmpoiele	Pg molasse; K_{1-2} sed. Fm.; J ophiolites; Metamorphites	hb α	hb α, mδp	unknown	K-fds, Pr, Ser, Ad, Ar, Im ar	HS, IS, LS 1. Cu-Au porphyry po ± cp stockworks /cylindric / drillcores L1 m0-1300 0.75 g/t Au and 0.76 %Cu. Maximum extension 1300m	po, py, cp	bt - qtz - K-fds - mt – py - cp; bt - qtz ± K-fds - py - po - mo; clm - py	12, 13, 17, 18
Larga – Horia level 516	K_2 -Pg molasse K_{1-2} flysch J ophiolites Metamorphites	hb α	hb α, mδp	unknown	K-fds, Pr, Ser, Ad, Ar, Im ar	HS, IS, LS 1. small Cu-Au porphyry po ± cp stockworks / cylindric 2. Au and Bi tellurides within small epithermal veins			12, 17
Bucium Tarniţa	K_{1-2} flysch Pre-Mz metamorphites	hb α	hb α, mδp	unknown	K-fds, Pr, Ser, Ad, Ar, Im ar				23
Roşia Poieni	K_1 flysch Pre-Mz metamorphites	hb-qtz α (Poieni type) as pyroclastics and intrusion	hb α, hb mδp (Fundoaia type)	hb-bi α, brown hb ± px α (9. 3 ± 0.50 Ma) as pyrocl. and small intr.	K-fds, Pr, Ser, Ad, Ar	HS 1. Cu-Au stockwork /elliptical / In vertical scale the mineralization between the elevation +1.180 - + 1.030 m → - 150 m, in horizontal plane are 660 m ÷ 740 m / 820 m ÷ 956 m / explored to 1200m / 431 Mt / 0.36% Cu, 0.29 g/t Au (level 550m > 0.4% Cu) 1.5 bil t of ore with 0.36% Cu 2. epitermal enargite pyrite veins	py, cp, mt / po, sph, gn, mo, cv, cc, ru	qtz - bt ± chl - anhy - mt - cp - py; qtz - chl - ill (+phengite) - sme -mixed layers - sme - kao - py; alu - kao - dic - pyro - dia - zun - mi -py - ena- gstel; qtz - pyro - dia - py; chl - alb - cb -ep - ser ± py	8, 15, 17, 21, 24
Poiana Ruscă Mountains									
Deva	K_2 sed.; Pz metamorphites	Bd-Sm detritic and cineritic rocks; hb α (12.6 ± 0.5 Ma), hb-bt α	bi-hb α (12.1 - 11.85 ± 0.5 Ma) polymictic breccia pipe	hb α, px-hb α	K-fds, Pr, Ser, Ad, Ar. Im ar	LS bo-cp stockwork / like overthrow cone	bo, cp, mt, py, Au, cc, cv, sph, gn	qtz - k-fds – bt – cp – bo – mt - py; bo - cub – cp - po - cp; anhy - ze - ca	13, 22

Abbreviations: *α – andesite, ad – adular, anhy – anhydrite, alu – alunite, ar – argillic, ap – apatite, bms – base metal sulfides, bt – biotie, cal – calcite, cb – carbonates, chl – chlorite, clm – clay minerals, cp – chalcopyrite, cov – covellite, dia – diaspor, dic – dickite, en – enargite, ep – epidote, gn – galena, K-fds – potassic feldspar, HS – high sulfidation, hb – hornblende, he – hematite, ill – illite, IS – intermediary sulfidation, Im.ar – intermediary argillic, ka – kaolinite, LS – low sulfidation, luz – luzonite, mc – marcasite, mδp – porhyry microdiorite, phy – phyllic, pr – propylitic, px – pyroxene, po – pyrrothite, py – pyrite, phyro – phyrophyllite, ru – rutile, qtz – quartz, ser – sericite, smec – smectite, sph – sphalerite, the – tetrahedrite, gstel – Au-Ag tellurides.*

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 (Săndulescu, 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 (Săndulescu, 1984). The nappe system from the western part of SAM (Groşi, Criş, Techereu – Drocea and Căbeşti (Lupu, 1972; Săndulescu, 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 – Stănija 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 (Ştefan *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, dacitic lava flows and ignimbrite rhyolites in the Vlădeasa Massif (Ştefan, 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 (Ştefan *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 thrusted within "Mid-" and Upper Cretaceous nappe piles (Bleahu *et al.*, 1981; Săndulescu, 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 Plopiş and Bihor Mountains in NAM (Berbeleac *et al.*, 1983; Ştefan *et al.*, 1986) and South beyond the Danube River, in eastern Serbia (Cioflica *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).

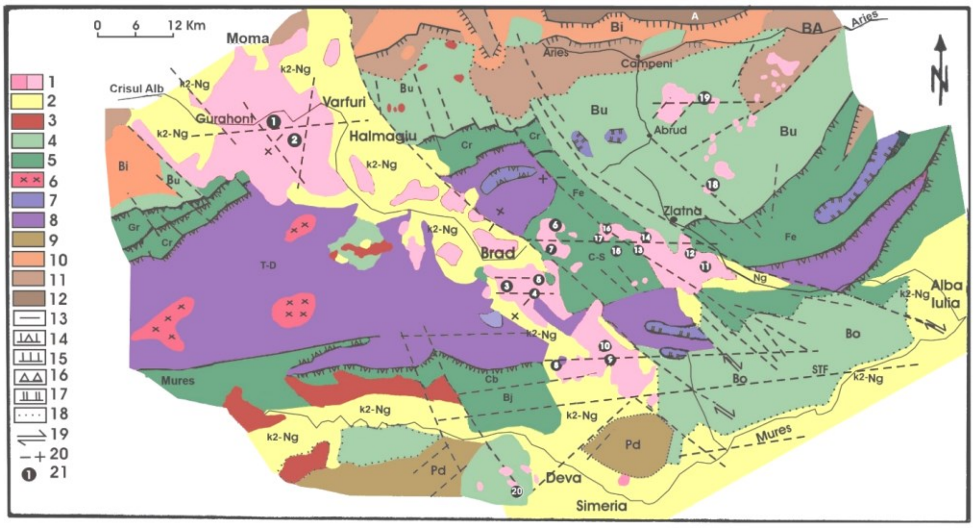

Fig. 2 – Geological map of Metaliferi and South Apuseni Mountains (from Berbeleac *et al.*, 2014). 1, Tertiary volcanic rocks; 2, Upper Cretaceous – Neogene sedimentary deposits (Faţa Băii Fm.); 3, Upper Cretaceous – Paleogene banatitic rocks; 4, Late Cretaceous sedimentary – volcanic rocks (mostly Bucium unit); 5, Early Crataceous sedimentary rocks (Feneş Fm.); 6, Jurassic granitoides; 7, Ardeu nappe and others; 8, Jurassic ophiolite; 9, Paleozoic Padeş crystalline shists; 10, Biharia nappe system; 11, Baia de Arieş series; 12, Finiş – Gârda nappe; 13, Geological boundary; 14, Upper Cretaceous – Paleogene nappes; 15, Pre-Gossau nappes; 16, Variscan nappes; 17, Mesocretaceous nappes; 18, Unconformity; 19, Thrust faults; 20, Normal fault and block movement; 21, Ore deposits/prospects.

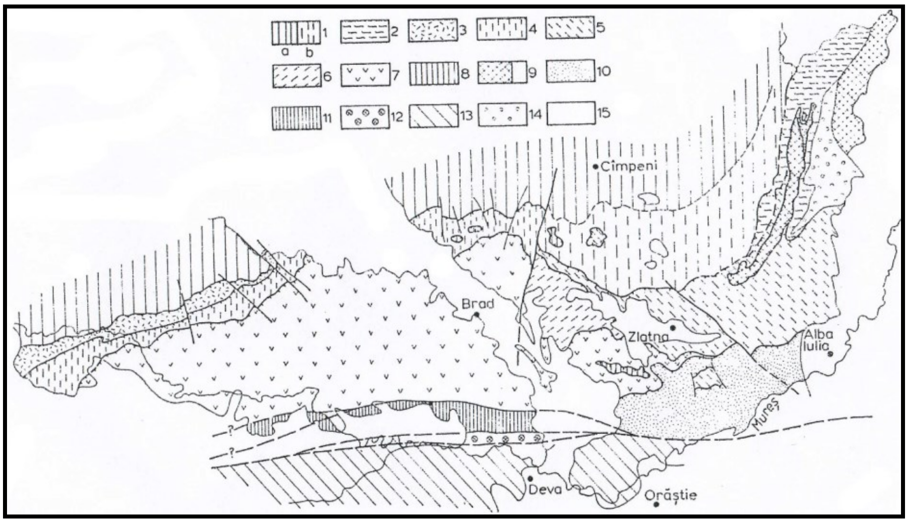

Fig. 3 – Tectono-structural map of central and southern part of the Apuseni Mountains (acc. to Săndulescu, 1984). 1, Biharia nappes system: a, metamorphic rocks; b, sedimentary rocks (Bucium); 2, Vidolm nappe; 3, Groşi nape; 4, Criş nappe; 5, Feneş nappe; 6, Curechiu – Stănija nappe; 7, Techereu–Drocea nappe; 8, Ardeu nappe; Trascău nappe; 10, Bozeş nappe; 11, Căbeşti nappe; 12, Bejan unit; 13, Supragetic nappes; 14, Remeşi Formation; 15, Post-tectonic basin.

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 Transylvanide unit (Săndulescu, 1984). Successive compression–extension events especially occurred along the contact between SC and SAM, reflected partially in the South Transylvanian Fault systems (Săndulescu, 1984) and Hălmagiu – Brad – Săcărâmb 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°, Pătraşcu *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 Hălmagiu – Brad – Săcărâmb 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), tuffites, volcanic conglomerates, dominantly hornblende quartz andesites in the Hărţăgani – Sălişte (Cioflica *et al.*, 1966) and Almaşul Mare – Zlatna areas (Borcoş, Vlad, 1994), known as Dealu Cornilor Formation. This formation is coeval with similar volcano–sedimentary deposits from ZM, and MM (Hălmagiu – Brad – Săcărâmb basin). The Dealul Cornilor Formation in Hărţăgani – Sălişte 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 (Săndulescu, 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 rations, negative Nb, Ta and Ti anomalies; lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ radiogenic isotopic rations). 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 – Gutâi – Ţibles arc segment of Carpathians area (Péckay *et al.*, 1995, 2000; Roşu *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; Roşu *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 Hălmagiu – Brad –Săcărâmb and Zarand basins. This formation consists of hornblende andesite, hornblende quartz andesite and dacite pyroclastics (breccias, 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 Hărţăgani – Sălişte 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 (14.6 ±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 Cetraş 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 Roşia 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, Ştirba) to large composite volcanoes with polystadial evolution, stratovolcanoes (*e.g.*, Tălagiu, Cetraş) 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, Cetraş – Măcriş, Bolcana, Musariu, Valea Morii Nouă, Colnic; Fig. 5), explosive volcanoes with vent breccia and diatreme-maar structures (*e.g.*, Roşia 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 – Almaşul Mare – Zlatna (12.81 ± 1.27 – 11.07 ± 0.63); 3) E–W, Roşia Montană – Roşia Poieni – Baia de Arieş; 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.

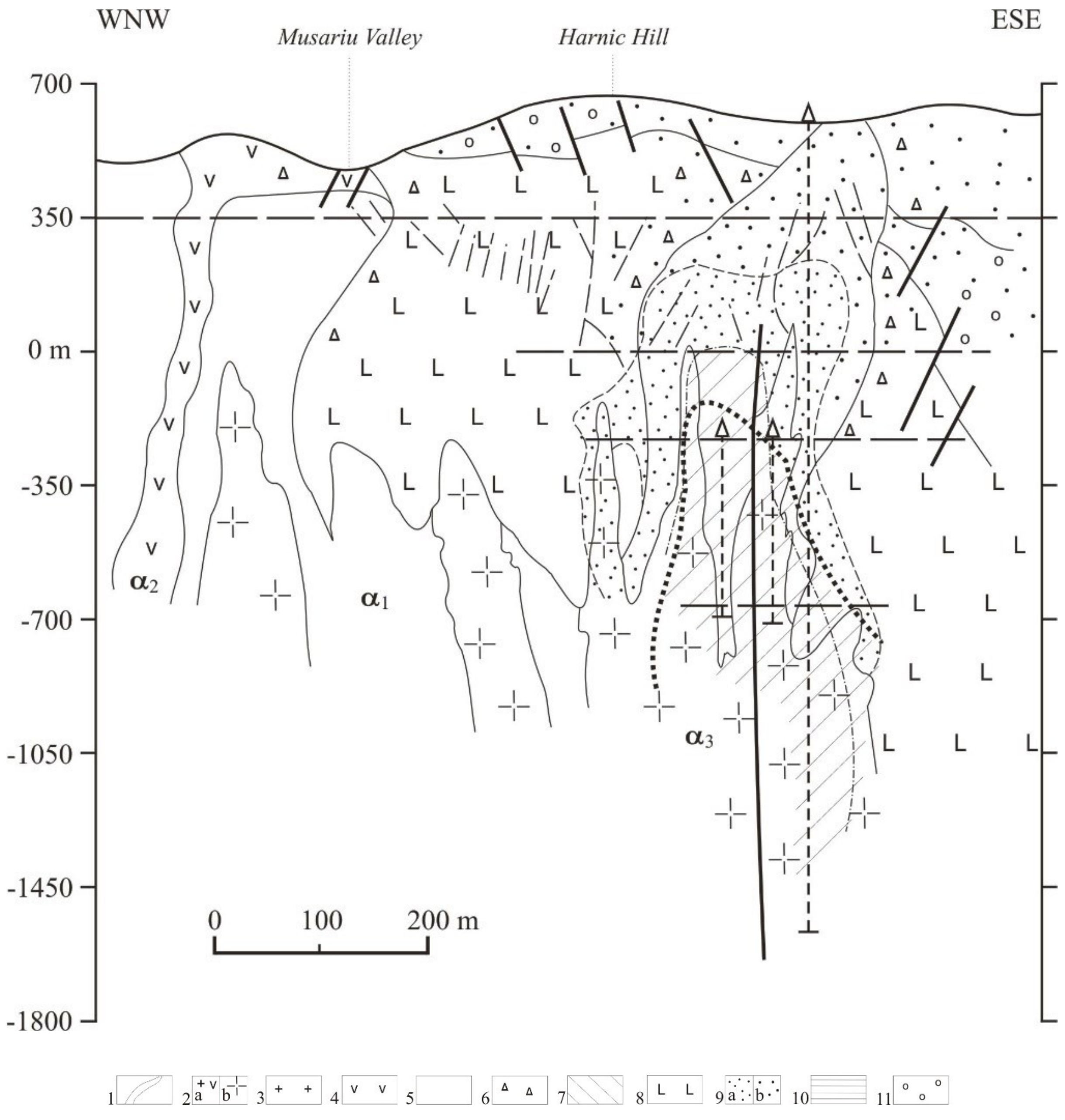

Fig. 4 – Simplified geological cross-section through Musariu gold deposits (from Berbeleac, 2003). 1, Sarmatian multi-stage subvolcanic intrusions: 2, Andesite-quartz andesite-porphyry diorite (a), Hb ± Px diorite (b); 3, Andesite (Barza type); 4, Upper Jurassic ophiolite; 5, Sarmatian andesitic and 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.

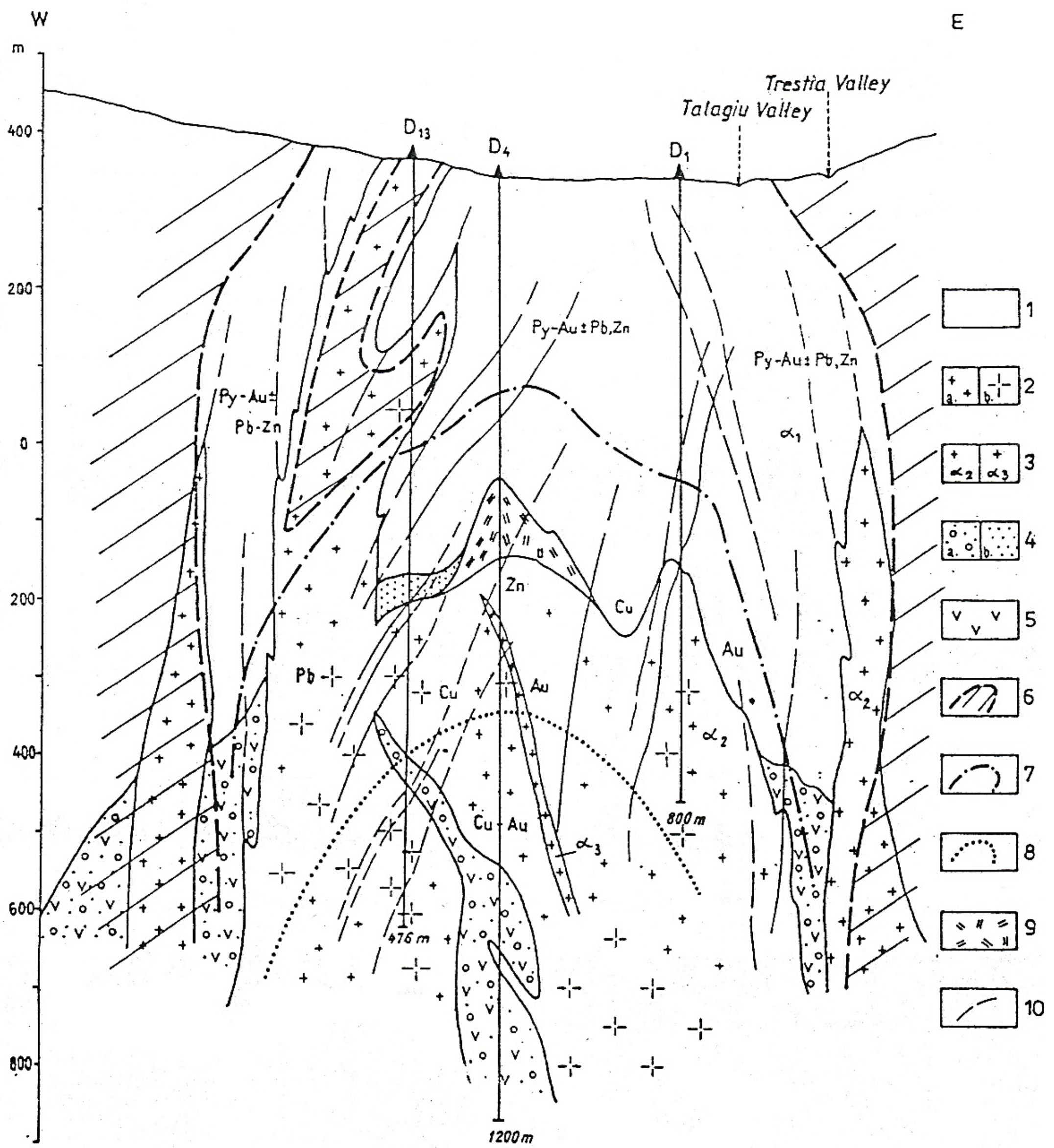

Fig. 5 – Geological cross-section within the Tălagiu area (acc. Berbeleac *et al.*, 1992). 1, lavas and volcanoclastic rocks; 2, hornblende-hypersthene-andesite (a), microdiorite porphyry (b); 3, pyroxene andesite (a), hornblende-hypersthene andesite (b); 4, conglomerate (a), sandstones (b); 5, hornfels; 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 hydrotermal 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 propyllitic 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 (Berbeleac *et al.*, 2014).

According to Roşu *et al.* (2004) most magmatic rocks are distributed along two alignments: one, of about 100 km long trending WNW–ESE between Miniş to the west, and Zlatna to the east and another, with ca. 60 km length between Deva to southwest and Baia de Arieş to northeast. According to Ciobanu *et al.* (2004) and references therein, the majority of 64 ore deposits/prospects from GQ occur within three main NW–SE trending volcanic alignments: Zarand–Brad–Săcărâmb, Zlatna–Stănija and Roşia 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 (Berbeleac *et al.*, 2010, 2015). The spatial configuration of the 20 porphyry systems is as follows: 2 prospects in the Tălagiu 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, Cireşata)–Bucuresci–Rovina (Remetea, Colnic) area, 1 deposit (Bolcana) and 1 prospect (Voia) in the Barbura–Voia area, 7 prospects in the Zlatna–Stănija area (Larga–Horia level 516 m, Trâmpoele, Popa–Stănija, Muncăceasca West, Valea Tisei and Runculeţe) and 2 deposits in the Roşia Montană–Bucium–Baia de Arieş area (Bucium Tarniţa and Roşia 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 diametres ranging between hundreds of metres up to 1 km (Voia, Bolcana, Valea Morii, Musariu), rarely exceeding 1 km (Tălagiu, Roşia Poieni). In vertical plane the bell shape is dominant. A particular shape of overthrow 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, Tălagiu), which are cross-cut by these intrusions. In some cases the volcanics have been eroded entirely and the stocks are hosted by Cretaceous (Roşia Poieni, Bucium Tarniţa, 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.*, Roşia Poieni, Bucium Tarniţa, Valea Morii, Musariu, Cireşata), 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 Roşia 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.*, Tălagiu, 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 Stănija, Bucium Tarniţa) and As–Cu (*i.e.*, Roşia 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.

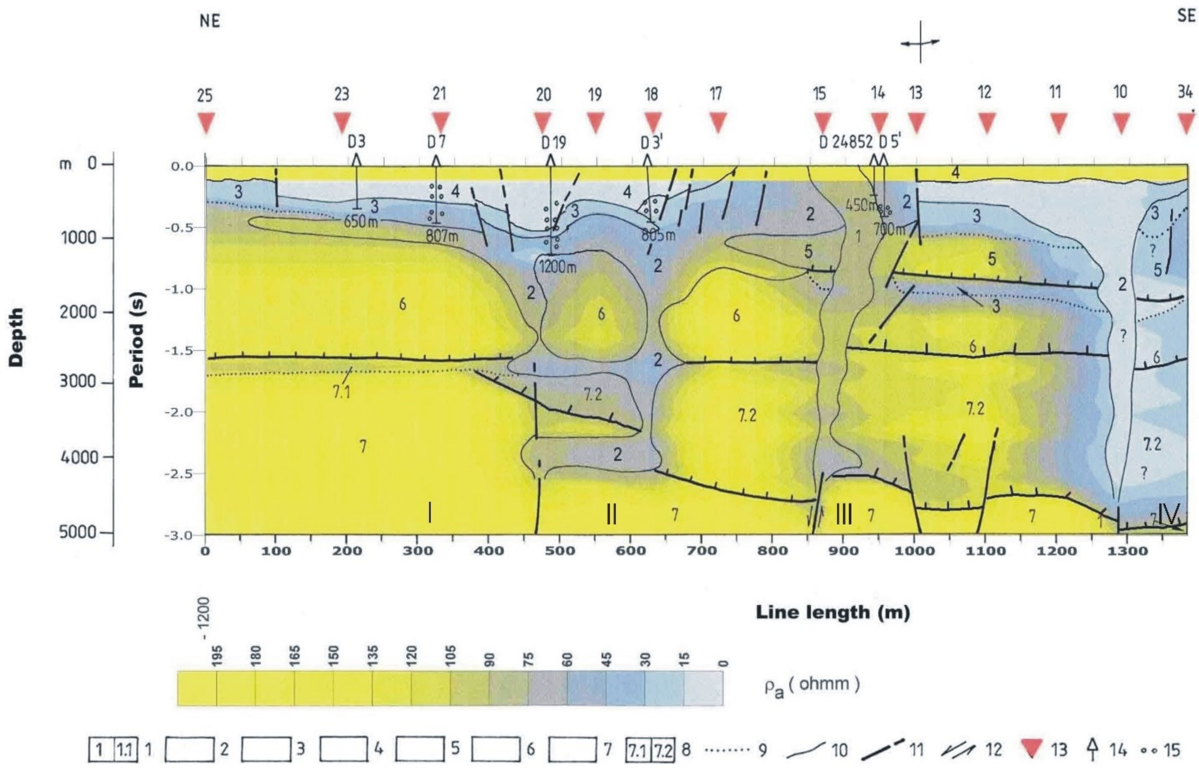

Fig. 6 – Resistivity profiles from Voia deep structure (acc. Berbeleac *et al.*, 2015). Legend: 1, 1 – Badenian–Sarmatian volcano-sedimentary rocks (a); 1.1 – incipient stage of alteration of crystalline schist (b); 2, Mineralized and alterated andesite-microdiorite intrusions; 3, Mezozoic sedimentary rocks ± mineralization; 4, Faţa Băii formation; 5, Ardeu nappe limestone; 6, Jurassic limestones of Drocea–Techereu nappe; 7, Crystalline rocks of Baia de Arieş nappe (?); 8, 7.1 – Bihor nappe (?) (a); 7.2 – Baia de Arieş nappe (?) (b); 9, Unconformity boundary; 10, Nappe; 11, Fault; 12, Sense of fault movement; 13, EMS; 14, Drill; 15, Porphyry copper mineralization.

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 Tălagiu 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 Tălagiu 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 (Babcock *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, Bolcana, Voia, Tălagiu, 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 Tălagiu 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 (Bolcana, Voia, Valea Morii, Roşia Poieni), (Berbeleac *et al.*, 1988, 2012b, 2014; Halga *et al.*, 2010), bornite (Deva – Boştinescu, 1984; Milu, 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 Bolcana (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 (Tălagiu, 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. Homogeneization 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.

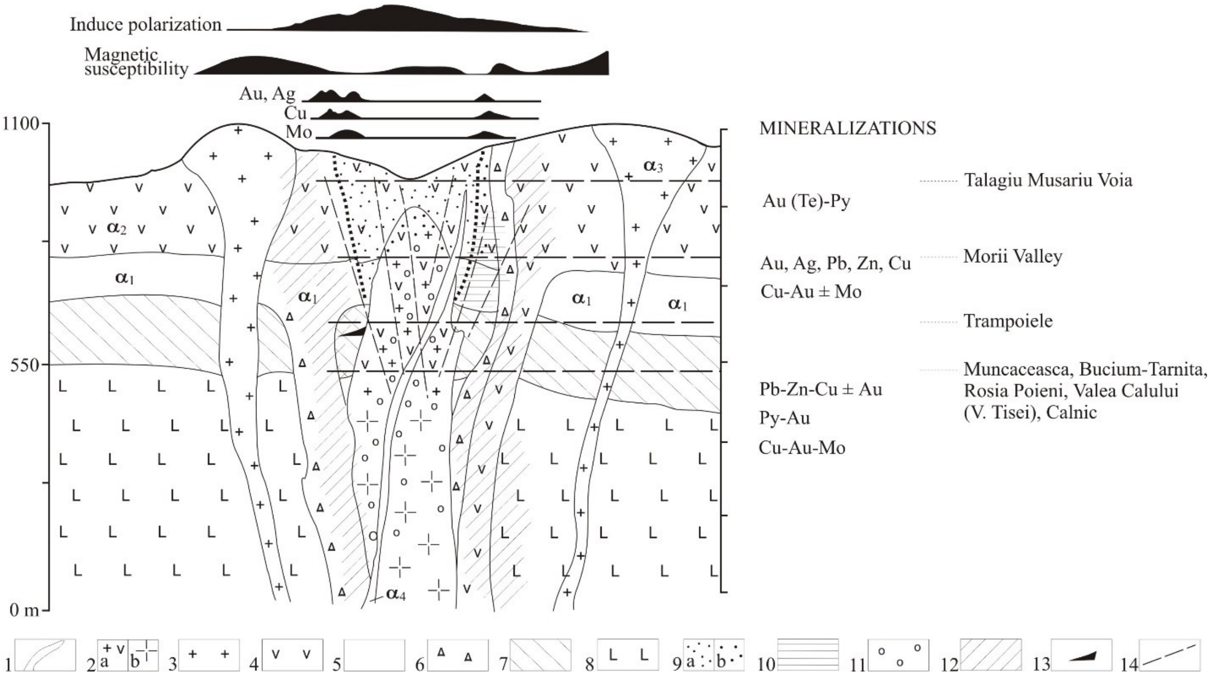

Fig. 7 – Generalized occurrence model showing intrusive and alteration relationships in porphyry copper–gold deposits and gold-base metal deposits from Zarand and Metaliferi Mountains. 1, Younger andesite; 2, Andesite (a) and porphyry diorite (b); 3, 4, 5, Other generations of andesites; 6, Breccia; 7, Sedimentary rocks; 8, Ophiolitic rocks; *Alterations:* 9, Argillitic intense (a) and intermediary (b); 10, Sericitic; 11, K-silicate; 12, Propylitic; *Mineralizations*: 13, Skarn; 14, Vein.

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; Borcoş, Berbeleac, 1983; Boştinescu, 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 (Borcoş, 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-gray colour and fine cryptocrystalline textures.

Small values of K_2O/SiO_2 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 (Al_2O_3 / K_2O + Na_2O + 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 Tarniţa = 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 (phyllic), 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 phyllic 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 and its the main mineral of multistadial and multidirectional network fissures besides K–feldspar, anhydrite, chlorite, pyrite, chalcopyrite, iron oxides and occasional free gold, bornite, cubanite, chalcocite, covellite, galena, sphalerite and molibdenite. Notable is the abundance in 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; Ivăşcanu, 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 feldspar, 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. Molibdenite 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 (Roşia Poieni, Bucium Tarniţa – 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 Tarniţa, Roşia 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^{-2}_4. 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, Roşia Poieni, Bucium Tarniţa), Jurassic ophiolites (Bolcana, Voia, Musariu, Valea Morii, Cireşata, Colnic, Rovina, Valea Tisei, Muncăceasca West and Trâmpoele), as well as sedimentary rocks of various ages: Jurassic – Cretaceous (Voia), Cretaceous (Deva, Colnic, Remetea, Roşia 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–Stănija, 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 ARGILLIC 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 Tălagiu (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 (Borcoş, 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 Tarniţa, 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, Tălagiu – 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, famatinite, and molibdenite. Argillic alteration represents the hallo with pyrite and marcasite of Voia–Pârâul lui Avram (Socolescu *et al.*, 1963; Udubaşa *et al.*, 1982), Dealul Talpelor–Cireşata (Ruff *et al.*, 2012) and Bratosin–Tălagiu Valley (Berbeleac *et al.*, 1982) porphyry systems. These are the largest argillic hallo 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; Trudu, 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 Roşia 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, Haneş, 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 Arieş);

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 Tălagiu achieved probably in two principal stages, such as: 1) thermobarric regime Th $\geq$ 700–750^{0}C, 200–250 bar, with hydrosaline melt (Na, Cl, KCl, $CaSO_4$, Fe_2O_3) and vapors ($H_2O+CO_2+H_2S$) (immiscibility), for the quartz pyrite I paragenesis and 2) anhydrite–pyrite II, the thermal regime dropping to 450–200°C with aqueous solutions ($SO^{2-}{}_4$ –Cl, Na^+, K^+, Ca^{2+}) and $H_2O+CO_2+H_2S$ vapors, followed by quartz II – pyrite II ± calcite during evaporation at T<200°C, further drops in temperature triggering vapors rich in H_2O, SO_4^{2-}, HCO_3^- 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 (Silitoe, 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 alkalic 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. Prospecţiuni S.A. and MINEXFOR, Deva, as unpublished geological reports cited in published papers (Borcoş, Berbeleac, 1983; Borcoş *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, Neacşu, 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 Roşia 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 (Roşia 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 stocks tending 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 (phyllic), 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 synchronuous 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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