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Porphyry and Epithermal Au-Cu Systems of the Southern Caucasus and Northern Iran

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ABSTRACT

This article presents tangible geological evidence for coexistence of porphyry copper and epithermal gold systems within single polygenic deposits and provides a paleothermophysical model for their origins. Brief metallogenic analysis of the Southern Caucasus and Northern Iran has shown that such deposits are confined to long-living calc-alkaline island arcs and were formed during their orogenesis. Examples of complex Sonajil (Iran), Gharta, and Merisi (Georgia) deposits are considered. Investigation has shown that for combined porphyry and epithermal ore formation some preconditions are suggested to exist: (i) Source of anomalous energy, which exceeds thermodynamics of the enclosing environment; (ii) Existence of temperature gradient, which determines conventional flows of fluids composed of endogenous and meteoric constituents (proven by rhythmical zoning of ore lodes); (iii) Stability of such conditions for a period of sulfide ore formation. However, such a process of sulfide ore formation cannot explain formation of high sulfidation gold deposits. Mass precipitation of free gold requires phreatic collapse in the ore conduit channel already after formation of hydrothermally altered rocks, and this event results in creation of either hydrothermal breccias, often with jigsaw-fit texture or brecciated vuggy silica where host rocks and hydrothermally altered rocks are cemented by a gold-bearing quartz matrix.

1. Introduction

By the end of the recent and the beginning of the new centuries our ideas on metallogenic setting and genesis of gold, copper and polymetallic mineralization of the Southern Caucasus and Northern Iran, as well as of the entire Tethys Belt as such, have dramatically altered. If formerly they were suggested to represent perhaps simultaneous but separate products of different ore-forming processes, today they are considered as deposits united by a common origin and separated from the mother magmatic hearths by different distances. For instance, the Southern Caucasus gold and base metal deposits were traditionally classified into volcanogenic gold & base metal massive sulfides of the Kuroko type, hydrothermal gold and polymetallic vein deposits and porphyry copper (with or without gold) stockworks (Tvalchrelidze, 1980; 1984). Such an approach significantly limited possibilities of new discoveries as exploration were based on false preconditions. As a result, the resource base of the regional stakeholder countries started to exhaust. For instance, in the beginning of the new Millennium gold resource base of Turkey was suggested to be extremely limited and prospects of new discoveries were pessimistic (Engin, 2003).

Identification of low, intermediate, and high sulfidation epithermal gold deposits, investigation of their typomorphic features and elaboration of a comprehensive methodology for their prospecting and exploration (Arribas, 1995; Hedenquist, 2000; Goldfarb et al., 2001; Payot et al., 2005; John et al., 2018; Wang et al., 2019, etc.) determined fast discoveries of new gold deposits in Turkey (Oyman et al., 2003; Diarra et al., 2019; Aluç et al., 2020; Gülyüz

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et al., 2020, etc.), the Lesser Caucasus (Bogdanov et al., 2013; Moritz et al., 2017; Veliyev et al., 2018; Imamverdiyev et al., 2021, etc.), and Iran (Mehrabi et al., 2008; 2014; Aghazadeh et al., 2015; Heidari et al., 2015; Sholeh et al., 2016, etc.). These discoveries were extremely important for improving the resource base of corresponding countries that is vital for their economic development (Tvalchrelidze, 2003). Correspondingly, the current statute of mining, for instance, in Turkey is significantly improved (Ersoy, 2022; Hastorun, 2022).

New metallogenic models have proven that either epithermal or porphyry deposits are related to development of calc-alkaline island arcs at the subduction and orogenic stages (Yigit, 2006; 2009; Mederer et al., 2013; Moritz et al., 2016, etc.).

Hence, as a rule, porphyry and epithermal deposits are described separately without paying any attention to possible genetic relation between them (Ghaderi et al., 2018; Kuşcu et al., 2019, etc.). Even models for these types of mineralization are generated separately (Sinclair, 2007; Taylor, 2007; Berger et al., 2008; John, 2010; John et al., 2018, etc.). In common, these models are based on typomorphic features of world-scale classical mines (see, for instance, Boomeri, et al., 2010). At the same time, already in 2000 R.H. Sillitoe outlined a genetic unity of porphyry copper and epithermal gold mineralization (Sillitoe, 2000). In the years that followed a lot of evidence on gold presence in porphyry copper ores were released (see, for instance, Shafiei and Shahabpour, 2008; Hajalilou and Aghazadeh, 2016, etc.). However, description of real, natural examples of telescoping and superposition of porphyry, low, intermediate, and high sulfidation epithermal systems are extremely rare, and I found no comprehensive, numeric models of such systems. That is why in this article I will both present tangible geological evidence for coexistence of such systems and try to provide a corresponding paleothermophysical model for their genesis.

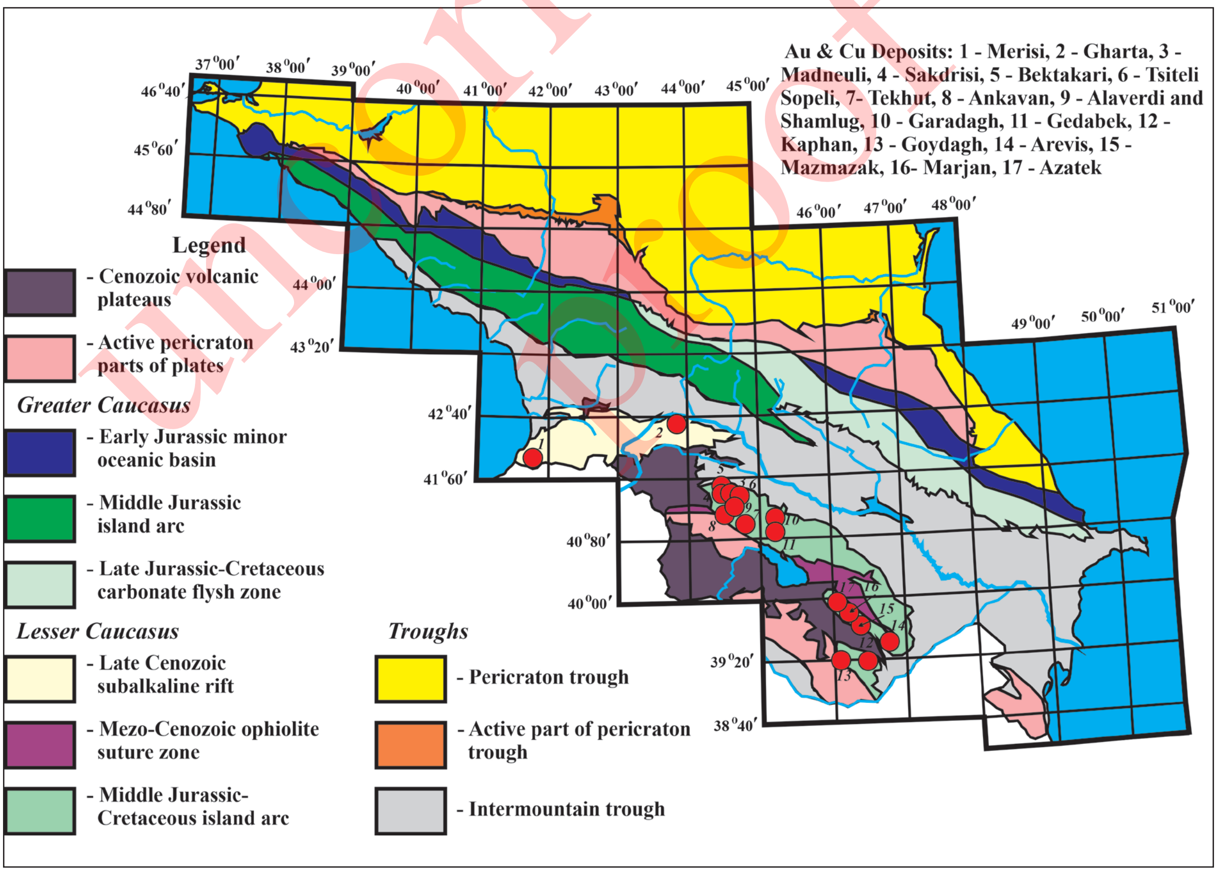

Figure 1 – Distribution of the most important porphyry copper (± gold) and high, intermediate, and low sulfidation gold deposits of the Caucasus. Map of metallogenic zoning is modified from Adamia et al. (2011) by author.

2. Metallogenic Setting of Epithermal and Porphyry Systems

2.1. The Southern Caucasus

Figure 1 describes distribution of epithermal gold and porphyry copper (± gold) systems of the Caucasus. It may be seen that the deposits are, firstly, distributed uniquely within the Lesser Caucasus, and secondly, they are confined to two tectonic zones. The first one is the Late Cenozoic rift zone (a so-called Adjara-Trialeti zone), which expands outside Georgia to Turkey (Adamia et al., 2011). This zone originated in Late Alpine (Paleogene-Neogene) time directly upon the Cretaceous cover of the Transcaucasian Median Mass (microplate), today overlapped by the intermountain through (Adamia et al., 1981). Within this zone Neogene homodrome basalt-andesite-rhyolite volcanism enlarges from the eastern edge of the rift (where tuffaceous sandstones and clays form a rhythmical series) towards the west (where typical basaltic and then andesitic volcanic flows are followed by rhyiodacitic and rhyolitic volcanic cones interlayered with tuffites). In the same direction alkalinity of the affinity gradually increases. In Late Neogene several quartz diorite to quartz monzonite massifs have been intruded predominantly in the central and western, tectonically more active, parts of the mentioned rift. Orogenesis occurred here by the end of Neogene, just before the Quaternary period. The described volcanic-plutonic affinity bears several typomorphic deposits with signs of porphyry copper ores in combination with epithermal either high sulfidation gold mineralization or intermediate sulfidation gold-polymetallic lodes. These types of mineralization will be briefly described below.

The second zone – Middle Jurassic-Cretaceous Island arc – is known as Somkhito-Karabakh zone of global extent (Tvalchrelidze, 1980; 1984). This volcanic belt covers territories of Armenia, Azerbaijan, Georgia, where it is covered by Cenozoic (Early Quaternary) andesite-basaltic nappes, and then continues to Turkey and beyond. The modern metallogenic model of this zone is elaborated by an international team of Swiss, Georgian, Armenian, and Azeri geologists (Mederer et al., 2013; Richards, 2015; Moritz et al., 2016; 2017).

Two volcanic-plutonic ore-bearing affinities are developed here. The middle Jurassic rocks lie directly upon the crystalline basement of the Transcaucasian median mass. The sequence starts with a basal conglomerate that overlaps Paleozoic granites. In Armenia and Azerbaijan, a thick calk-alkaline subaqueous andesitic volcanic-sedimentary series is developed. But north-westward, towards Georgia, this island arc affinity decreases its thickness, and manifestations of Middle Jurassic volcanism become rare. In Bathonian time this affinity was intruded by huge quartz diorite bodies. One of them, the Shnokh-Kokhp massif, controls the world class Tekhut Au-Cu porphyry mine (no 7 on Figure 1) with ore reserves of 460 million tons and copper grade of 0.35% (Marutani, 2003). Cretaceous sediments in Armenia and Azerbaijan are presented only by limestones with insignificant thickness.

Towards Georgia, on the contrary, thickness of Cretaceous rocks is sharply increased. Here a thick ore-bearing Cretaceous andesitic (minor basalt-andesite-dacite-rhyolite) calk-alkaline formation created numerous central-type volcanoes and vast fields of acid subaqual pyroclastics in intervocalic areas. This sequence is especially thick (up to 1-1.5 km) within the Bolnisi Mining District, which hosts the great majority of the country's gold and copper reserves (no 3-6 on Figure 1). The sequence is intruded by several quartz diorite bodies the significance of which in ore formation is discussed below.

Among the deposits of the Bolnisi Mining District the largest is Madneuli intermediate sulfidation mine with primary ore reserves of 93.1 million tons and metal inventories in them: copper – 542 thousand tons; zinc – 79.8 thousand tons; lead – 8.2 thousand tons; silver – 134 tons; gold – 53.8 tons (Tvalchrelidze, 2003). The mine is the main copper and gold producer in Georgia.

Petrology of both Middle Jurassic and Cretaceous volcanic-plutonic affinities was described in detail some 35 years ago (Tvalchrelidze, 1987).

2.2. Northern Iran

Figure 2 analyses distribution of some typomorphic porphyry copper (± gold) and mainly high sulfidation gold depo its of Iran. These deposits include world class mines, such as Sungun (no 1 on Figure 2) with recoverable ore reserves of 861 million tones and copper grade of 0.6% (Hosseini et al., 2017), and Sarcheshmeh (no 11 on Figure 2) with ore reserves of 1,538 million tons with copper grade of 0.58% (Boomeri et al., 2010).

It may be seen on Figure 2 that all typomorphic deposits without exception are related to the Urmia-Dohtar metallogenic zone. The latter represents an andesitic island arc, which has undergone orogenesis in Late Neogene – Early Quaternary. In eighties of the recent century extremely extensive development of orogenic magmatism with still active volcanoes like Sakhand and Sabalan was not understood (Berberian and King, 1981) but today it is clear that this zone still is subject to continuing subduction under the Iranian Microcontinent (Kaviani et al., 2009).

In Northern Iran the Urmia-Dohtar zone is overlapped by Early Quaternary basaltic nappes and borders with Alborz magmatic belt at north and with Sonandaj-Sirjan metamorphic at south-west. The latter represented a rift zone, which has undergone orogenesis and metamorphism before Alpine time (Kaviani et al., 2009; Richards, 2015).

Thus, both in the Southern Caucasus and Northern Iran porphyry copper-gold as well as epithermal ore-forming systems are related to long-living island arcs, which have undergone relatively continuous subduction followed by active development of orogenic magmatism. As a rule, these systems form individual porphyry, high, intermediate, and low sulfidation deposits but seldom deposits bear features of different mineralization types. Below such examples are considered.

3. Combination of Ore-Forming Systems

3.1. Porphyry and High Sulfidation Systems – Sonajil Deposit, Northern Iran

Sonajil Deposit is situated in East Azerbaijan Province of Iran, near Heris city, in 85 km from Tabriz – the province capital. The deposit was and still is being explored by our international team. By today, recoverable reserves of high sulfidation gold ores were estimated, and gold-producing open pit mines, a heap, and a Carbon-in-Leach (CIL) plant are under construction. Estimated total resources of the gold-bearing site equal to 7.6 million tons with gold grade of 1.5 g/t hosting 361 thousand troy ounces of the metal. Porphyry copper ores are under extensive exploration now. All the 12 drilled boreholes cut porphyry ores with an average copper grade of 0.4%. Today, the explored vertical interval of mineralization exceeds 600 m. In boreholes the first signs of gold presence with commercial grades were fixed.

Figure 3 demonstrates the model geological map of Sonajil deposit. The geological structure of the deposit is complex enough. The geological section starts with Eocene volcanic suite of basalt-andesitic trend, which consists of basalt and andesite lavas, volcanic breccias of the same composition, tuffs, and tuffaceous volcanic-sedimentary rocks. In the ascending section this suite is replaced by Miocene sandstones and marls.

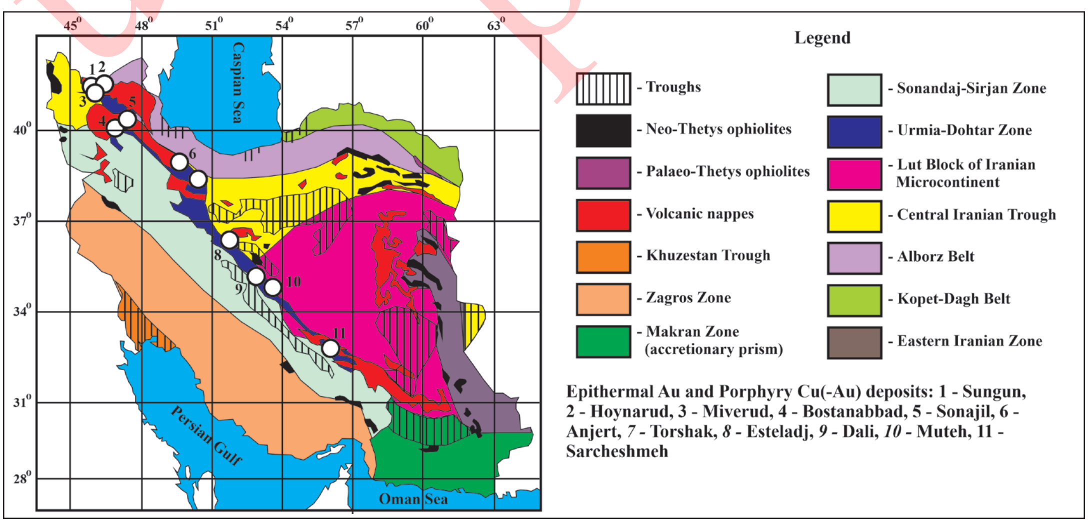

Figure 2 – Distribution of typomorphic porphyry Cu (± Au) and epithermal gold deposits of Iran. Map of metallogenic zoning is drawn from Kaviani et al. (2009) modified by author.

The overall sequence terminates with Early Quaternary volcanic flow of basalt & dolerite composition, which occupies the highest hypsometric level of the terrain.

Eocene volcanic sequence is intruded by two stages of an igneous complex. Outcrops of two phases of the Inchekh intrusive body are observed in the central part of the area. The first phase is composed of alkali rocks – monzonites and syenites whereas the second phase consists of calk-alkaline quartz monzonites and microdiorites. The rocks have porphyry structures and may be interpreted as a root part of a volcano. The younger Sonajil intrusive stage has a well-expressed hypabyssal character and is presented by mica granites and monzonites.

The deposit consists of two sites. The site of epithermal high sulfidation gold mineralization is situated 4.5 km south-westward from the porphyry copper site. The ore-bearing structure of the site has a north-westward trend (azimuth 320-340°), length about 1,400 m, width from 10 to 50 m and incidence angle 45-60° to the west-south-west. Ore mineralization is traced up to the depth of 200 m from surface. Within the site the gold-bearing body is presented by a hydrothermal breccia where fragments of hydrothermally altered (quartz + sericite) andesites are cemented by grey quartz. Quartz (seldom accompanied with calcite) matrix of breccias has huge thickness (over than 200 m) from surface. The breccia has a jigsaw-fit texture (Figure 4a) the origin of which was described in detail in many publications (see, for instance, Cas et al., 2011).

Porphyry copper site, situated in the north-eastern part of the deposit, is presented by typical medium-grade ores in hydrothermally altered (quartz + enargite) intrusive rocks, mainly diorites of both Inchekh and Sonajil intrusive bodies (Figure 4b). The orebody is under extensive drilling campaign because prospects to discover a world class copper-gold deposit are very high.

Thus, the basic features of the deposit, important for further discussion, are as follows:

1. Porphyry and high sulfidation epithermal sites are separated in space.

2. Gold mineralization occurs in hydrothermal breccia formed later than country andesitic rocks were hydrothermally altered.

3.2. Vertical Zoning of Epithermal High Sulfidation and Porphyry Systems – Gharta Deposit, Georgia

Gharta deposit is located in Kareli District, Shida Kartli Region of Georgia, in 152.5 kilometers from the capital of Georgia – Tbilisi City, at the northern slope of the Trilaleti Ridge, Lesser Caucasus. Metallogenically it belongs to the north-eastern edge of the Adjara-Trialeti rift zone (no 2 on Figure 1). The deposit is subject to extensive exploration by our international team. By today, after having covered by a drilling campaign only about 15% of the deposit's area, we already have identified 9.1 million tons of

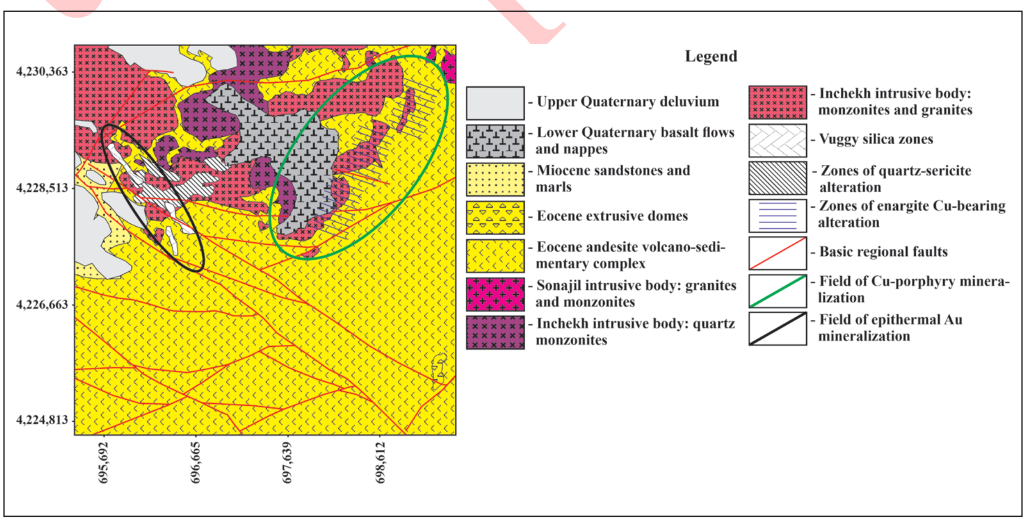

Figure 3 – Model geological map of Sonajil deposit, This study.

high sulfidation gold ores with average gold grade of 0.93 g/t and 62.8 million tons of porphyry copper ores with average copper grade of 0.42%. Figure 5 represents a model geological map of the deposit.

The geological structure of the deposit represents an area covered by outcrops of a Late Neogene intrusive body of quartz diorite composition, which has intruded Paleogene-Lower Neogene rhythmical slates, argillites and aleurolites as well as Upper Cretaceous chemogenic limestones. Host rocks are mainly preserved as relicts within the intrusive body, and only in the north-western part intrusive contact with the mentioned rhythmical slate suite is observed. Numerous, mainly sub-latitudinal faults, have steep, subvertical dip. The entire structure, including the ore zone, is inclined to the east under the angle of 35-45°.

The ore zone has an irregular ellipsoid shape and is presented by hydrothermally altered rocks solely developed in intrusive rocks. Two contrast types of metasomatics were identified. Within epithermal gold bonanzas, developed at upper horizons in the western flank of the mineralized zone, hydrothermally brecciated and often fractured vuggy silica is developed (Figure 6a), where debris of quartz diorite and early products of its hydrothermal alteration – quartz-sericite rocks, are cemented by grey quartz. At deep horizons porphyry copper ores are hosted by high temperature quartz-sericite-garnet rocks with intense development of epidote. Very often development of garnet (difractometrically – andradite) is so strong that quartz diorites are altered to a monomineral “garnetite” (Figure 6b).

A well pronounced vertical zoning is characteristic of the deposit (Figure 7). At upper horizons epithermal high sulfidation gold ores are developed. Beneath 100 m from surface ores are enriched with chalcopyrite, which sometimes creates high graded ores (Borehole BHG-03 on Figure 7). At deep horizons gold-free porphyry copper ores are presented. It is extremely important to note for the further discussion that between gold and copper ores always an ore-free space exists.

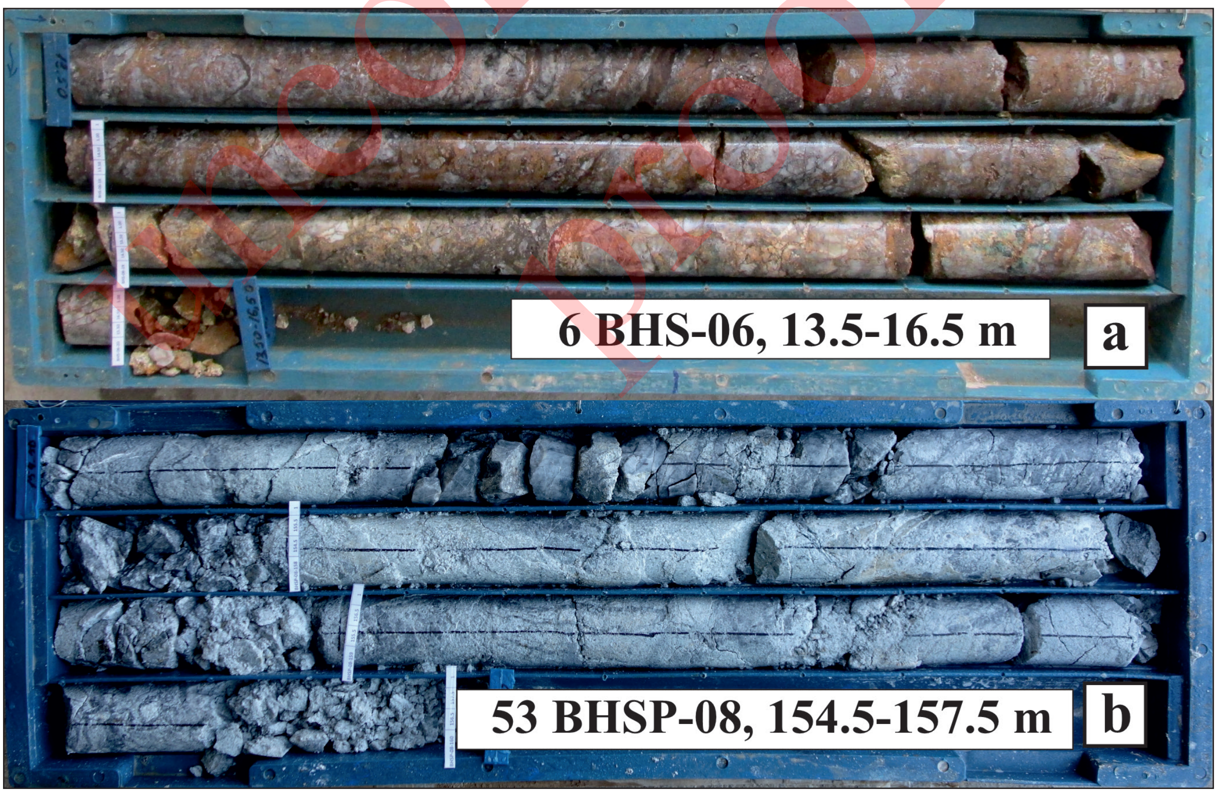

Figure 4 – Typical ores of Sonajil deposit, a) gold ores presented by thin impregnation of free gold in the hydrothermal breccia with jigsaw-fit texture; debris of hydrothermally altered quartz-sericite rocks are cemented by quartz. Average Au grade of the interval is 1.41 g/t. b) porphyry gold-copper ores in hydrothermally altered diorites. Average grades of the interval: copper – 0.56%, gold – 0.74 g/t.

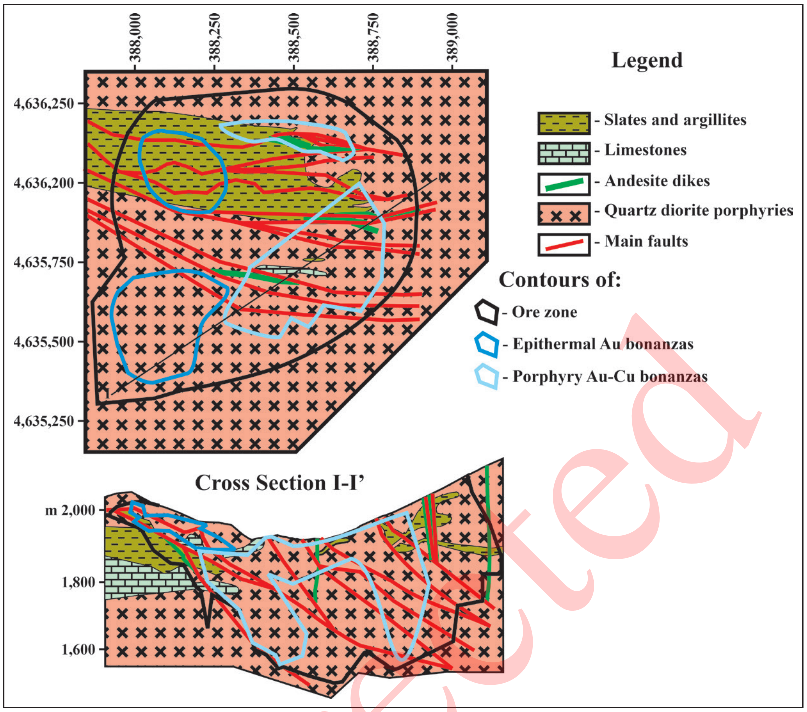

Figure 5 – Model geological map of Gharta deposit. This study.

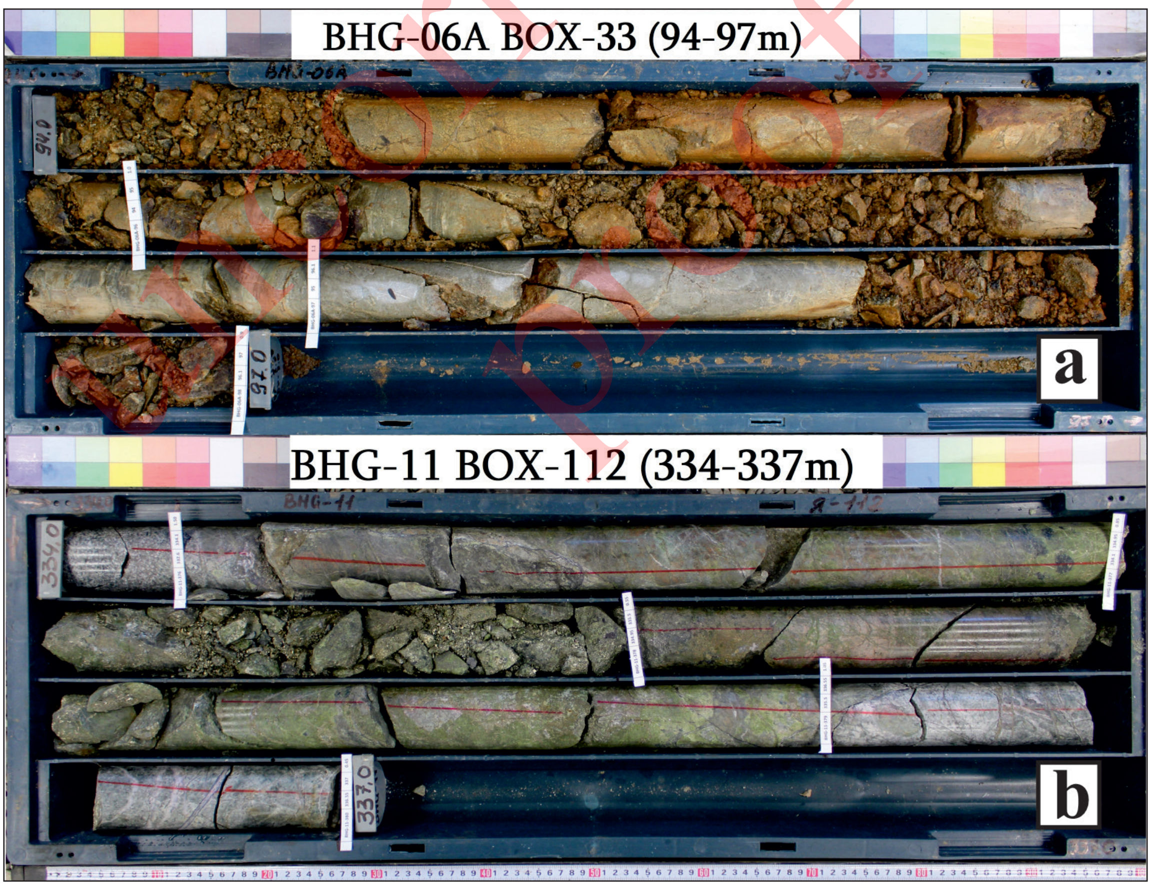

Figure 6 – Typical epithermal high sulfidation gold and porphyry copper ores, a) brecciated and fractured vuggy silica; average gold grade of the interval – 3.70 g/t, b) quartz-sericite-garnet (andradite) rock with epidote (green) nests; average copper grade of the interval – 1.38%.

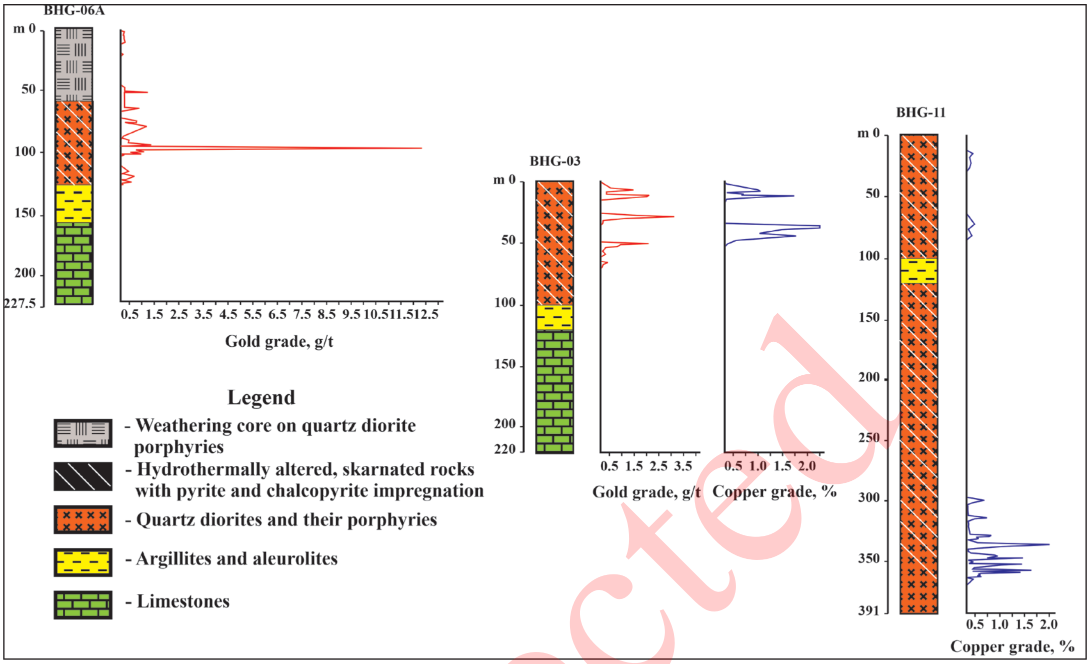

Figure 7 – Vertical zoning of Gharta deposit.

3.3. Intermediate Sulfidation and Porphyry Copper Systems – Merisi Mining District, Georgia

Merisi mining district (no 1 on Figure 1) is located in mount Adjara, in 60 rm from Batumi – capital of Adjara Autonomous Republic of Georgia, just on the state border with Turkey. The mining district was explored in 30ies – 60ies of the recent century but copper mining was performed even during the First World War. Today, only vein-type intermediate sulfidation gold-bearing small deposits were explored but the main prospects of the district are related to the porphyry copper system and possible presence of high sulfidation gold ores. Thus, the district is a favorable target for exploration.

Figure 8 contains information on the geological structure of the mining district. The mining district was mapped by the author together with his post-graduate student, now Professor Archil G. Magalashvili, and afterwards described in detail in my monograph (Tvalchrelidze, 2006).

The central part of the mining district is composed of the Merisi-Namonastrevi intrusive complex, which covers an area of 17 km^2 and forms three outcrops: (i) Merisi outcrop with area of 7.5 km^2, (ii) Namonastrevi outcrop (6.5 km^2), and (iii) Chalati outcrop (2.5 km^2). Detailed petrochemical investigations as well as fault mapping have proven that Namonastrevi and Chalati outcrops were uplifted along the sub-longitudinal fault on about 800 meters (Tvalchrelidze, 2006) causing manifestation of different acidity rocks in its western and eastern flanks: Rocks of the main intrusive phase in Merisi outcrop are more acid compared with those of Namonastrevi and Chalati outcrops. The same investigations demonstrated that the second, quartz diorite porphyry, phase intruded after the displacement along the mentioned fault already took place: Rocks of this phase are the same in either outcrop. At least, fluid porphyry breccia phase, in my opinion, marks the center of the porphyry ore-forming system and may serve as a tangible exploration sign.

All intermediate sulfidation gold & base metal epithermal deposits and occurrences have a standard structure. Firstly, they are separated by a certain distance from the contacts of the intrusive massif. Secondly, they form solely in country rocks subvertical lodes of quartz ± barite composition, which have different thickness, from first meters up to 20 meters but in average – 2-3 m. This matrix bear impregnation and nests of sulfides – mainly pyrite, chalcopyrite, galena, sphalerite but also sulfosalts including sulfoantimonites, patrinite, clausthalite, etc. Near the surface sulfides are oxidized to bornite, hematite, etc. Gold is presented both in a native form as thin impregnation in ores and as admixture in iron, copper, lead, and zinc sulfides. Ore lodes are followed by thin gouge-like halos of typical medium temperature hydrothermal alteration presented by a quartz-sericite-chlorite rock. Ores are characterized by a breccia texture.

Peculiarities of porphyry, high, and intermediate sulfidation systems, described here, compose a solid base for further discussion.

4. Discussion

Investigation of the thermodynamic conditions for evaluation of hydrothermal systems from a porphyry stage to the low sulfidation one has been performed by Einaudi and his co-authors (2003). I have performed approximately the same type of studies sixteen years before (Tvalchrelidze, 1986; 1987). For instance, Figure 9 represents a thermodynamic plot demonstrating equilibria between the crystallizing minerals and a model hydrothermal fluid under the temperature of 250°C.

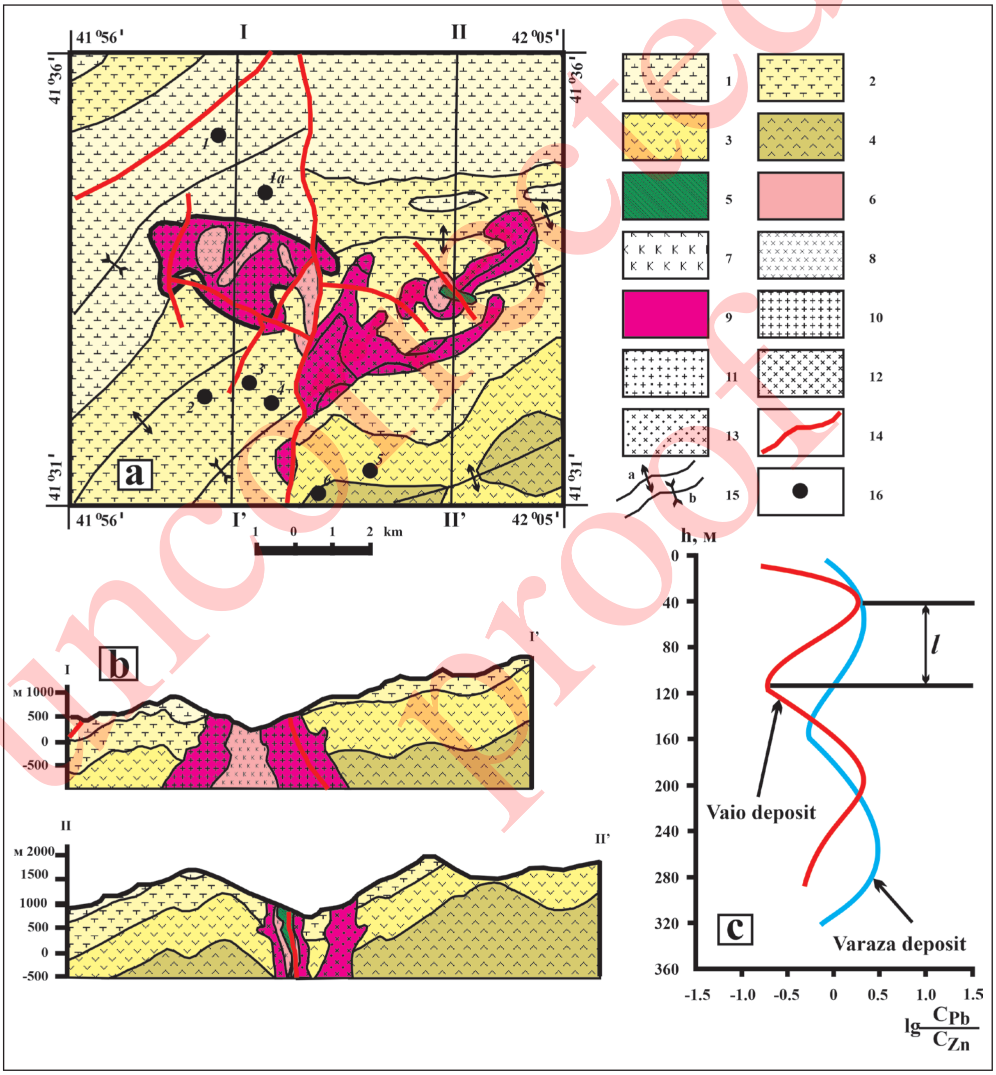

Figure 8 – Geological structure of the Merisi mining district, a) geological map; b) cross sections to it. Legend: 1 – Upper Eocene – Oligocene: trachybasalt lavas; 2 – Upper Eocene: calc-alkaline basalts and tuffs; 3 – Middle Eocene: subalkaline basalt-andesite-dacite volcanics; 4 – Middle Eocene: andesite tuffs; 5-13 – intrusive rocks: 5 – fluid porphyry breccia phase, 6-8: quartz diorite porphyry phase: 6 – subvolcanic bodies, 7 – quartz diorite porphyries, 8 – quartz diorites; 9-13: main intrusive phase: 9 – the main intrusive complex, 10 – alaskites, 11 – granite porphyries, 12 – monzonites, 13 – diorite porphyries; 14 – basic faults; 15 – a) anticline and b) syncline axes; 16 – intermediate sulfidation gold & base metal lodes: *1* – Vaio, *1a* – Surnali site of Vaio, *2* – Veliburi, *3* – Verkhnala, *4* – Tskalbokela, 5 – Varaza, *6* – Obolo-Kanly-Kaia, c) vertical rhythmical zoning of lodes. *l* – pitch of rhythmicity, C_{Pb} and C_{Zn} – grades of lead and zinc, correspondingly.

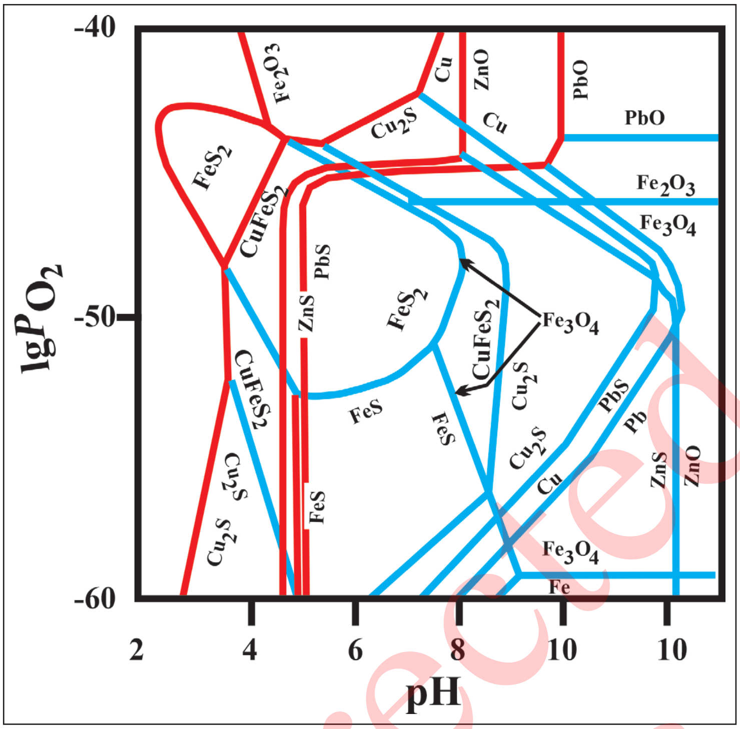

Figure 9 – Equilibria of iron and base metal minerals with a model hydrothermal fluid at 250°C. Parameters of the model fluid were published earlier (Tvalchrelidze, 1987). Blue lines – equilibria between solid phases; red lines – equilibria between solid phases and a model fluid.

Analysis of this plot leads just to the same main conclusion made by Einaudi et al. (2003): Development of the system and gradual crystallization of minerals occur at the background of the fluid neutralization. However, such a type of analysis is unable to explain neither origination of conventional fluid flows nor ore formation, e.g., mass precipitation of ore minerals within the comparatively limited time period in the comparatively limited space. Moreover, basic typomorphic features of epithermal systems are not considered.

A certain time ago I have analyzed data on enormous number of vein deposits and have proven that practically all of them are characterized by a rhythmical zoning meaning that grade ratios of main ore-forming metals undergo rhythmical undulations in the vertical section (Tvalchrelidze, 1993). Here this event is demonstrated for two deposits of the Merisi mining district (see Figure 8c). The pitch of such zoning *l* is proportional to the overall vertical interval of the lode. Further, I have proven that this phenomenon is determined by ore formation in non-equilibrium conditions under guidance of a thermal gradient. In such environment metal cations tend to be tied by sulfide-ion, and different reactions of metal sulfides' precipitation compete with each other, for instance, as it is shown in equation (1):

$$
\begin{aligned}
Zn^{2+} + S_2^{2-} &\xrightarrow{k_1} ZnS \\
Pb^{2+} + S_2^{2-} &\xrightarrow{k_2} PbS
\end{aligned} \qquad (1)
$$

Correspondingly, kinetic coefficients k_1 and k_2 depend on the oversaturation degree of corresponding metals. Based on this simple assumption, I have elaborated mathematical and thermodynamic models of such non-equilibrium reactions and formulated the theory of rhythmical zoning (Tvalchrelidze, 1993). This theory illustrated distribution of bonanzas and vertical zoning of ore lodes but was unable to explain formation of gold ores in epithermal high sulfidation deposits.

Indeed, as it is shown on Figure 10, gold remains dissolved in a hydrothermal fluid within a vast range of P-T conditions. It is suggested that this phenomenon is related to dual position of gold within the common acid-alkali range of metals.

Firstly, gold is encountered together with iron in slightly acid fluids. Secondly, it is deposited from low temperature fluids at the final stages of ore formation (Kolonin, 1983). This peculiarity may simply be explained by the fact that gold has a well-expressed chemical affinity with arsenic (Marakushev and Bezmen, 1970), which, in turn, in a high temperature fluid is presented in form of the acid at the line of monovariant equilibrium between hydrogen sulfide and sulfuric acid (see Figure 10). However, in a low temperature fluid arsenic plays the role of a metal. Correspondingly, gold plays no role in competitive sulfide deposition processes, gradually precipitates from a fluid with fall of temperature creating concentrations far below the cutoff grade and in normal evolution of high sulfidation hydrothermal systems is unable to form mineral deposits.

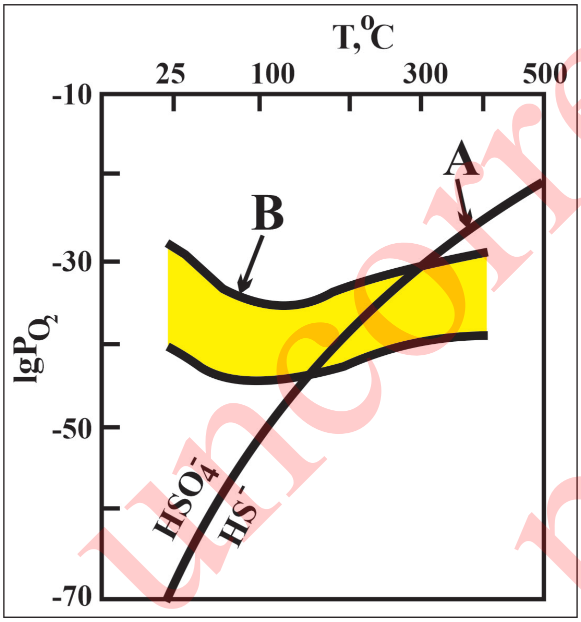

Figure 10 - Partial pressure of oxygen during crystallization of base metal sulfides and barite. After Tvalchrelidze (2006), A – monovariant equilibrium Line between S^{6+} and S^{2-} B – field of gold stability in a hydrothermal fluid.

Thus, the sole reason for gold precipitation when a high and/or intermediate sulfidation epithermal mineralization is formed, is a sharp failure of the consecutive ore formation process due to external reasons. One of such reasons is phreatic collapse of the ore-hosting structures with subsequent boiling of the hydrothermal fluid and mass precipitation of its ore charge.

The presence of hydrothermal breccias often with jigsaw-fit texture in ores, specially outlined by us (see Figure 4a), or of vuggy silica (see Figure 6a) is evidence of such a collapse. Thus, hydrothermal breccia has a phreatic character. It should be noted that such phreatic breccias were often described in models of high and/or intermediate sulfidation systems (see, for instance, Wang et al., 2019).

However, several features characteristic of either porphyry or epithermal systems do not fit with the purely thermodynamic approach. Namely:

1. Intermediate and low sulfidation mineralizations, as a rule, are located at a certain distance from the contacts of the intrusive body. Moreover, I have demonstrated that this distance directly depends on dimensions of the plutonic massif (see, for instance, Tvalchrelidze, 2006).

2. Direct transition between porphyry and high sulfidation ores is never observed. In any case, I have never seen such a transition in any deposit and never heard or read about them. I have specially shown that between porphyry and high sulfidation ores a certain ore-free space exists (see Figure 7), though this interval is hydrothermally altered just in the same manner and with the same intensity as in ore bonanzas.

3. Porphyry copper ores are often hosted by the main intrusive body and therefore were formed when the latter has entirely been crystallized. Accompanying high sulfidation gold ores have the same age, and intermediate and low sulfidation manifestations may be their simultaneous or a bit younger. These intrusive bodies when crystallized had a distinct depth, not less than one kilometer, and therefore, had no subvolcanic roots. Therefore, for such combined systems a common model of high and low sulfidation systems nourished from a peripheric magmatic hearth, are not applicable.

That is why it seems to be important consideration of the paleothermophysical models of cooling intrusive bodies.

One of pioneers of such investigations was my course mate in Moscow State University, Doctor of Geology and Mineralogy Vladimir G. Zolotarev who came to a tragic end with all his family in a car accident in the early nineties of the recent century. In his memory, I continued his investigations and created a model of the Merisi mining district.

In a few words, Dr. Zolotarev's approach is based on some simple realities (Zolotarev, 1985, etc.): When intruded, the magmatic fusion has a temperature which greatly exceeds those of country rocks. That is why, according to the Second Rule of thermodynamics, heat exchange between magma and host rocks immediately commences – magma is being cooled and crystallized, and country rocks are being heated. Modelling of such fields must be based on the classical Fourier's equation of heat and mass transfer and may be described as a sum of convective and conductive flows of heat and mass:

$$C\rho(\frac{\partial T}{\partial t}) = -\nabla(q_L h_L + q_S h_S) + \nabla(\lambda \nabla T) + F' \qquad (2)$$

Where: ρ = density, C = heat conductivity, T = temperature, t = time, λ = heat conductivity factor, h_L and h_S = enthalpy of fusion's liquid and gaseous phases, q_L and q_S = fusion and liquid phases masses, passing through the elementary 1 cm² section, F' = latent fusion heat determining phase change, ∇ = Hamilton's operator. In 3D Descartes space the latter may be expressed as:

$$\nabla = (\frac{\partial}{\partial X} + \frac{\partial}{\partial Y} + \frac{\partial}{\partial Z}) \qquad (3)$$

Zolatarev (1985) has proven that in thermophysical models of a cooling magmatic body the influence of the convective member of the Fourier's equation is negligible. In this case, development of the heat field through time may be described by the classical equation of heat transfer:

$$C\rho(\frac{\partial T}{\partial t}) = div(\lambda gradT) + F'(x,y,z) \qquad (4)$$

It may be easily proven that equation (4) is of an exponential type and has no analytical solution. That is why modelling of heat fields should be completed according to an approach elaborated by Zolotaev (1985, etc.). The overall geological space may be divided into a necessary number of elementary blocks having homogenous composition and exact coordinates in the Descartes space. Then, the heat transfer equation should be solved for each elementary block separately:

$$C\rho(\frac{\partial T}{\partial t}) = \lambda(\frac{\partial^2 T}{\partial t^2}) + F' \qquad (5)$$

And for each time interval *Dt* heat amount (*DQ*) may be calculated for each block having coordinates *i*, *j*, *k*, and the block will have temperature:

$$T'_{i,j,k} = T_{i,j,k} + \Delta T; \Delta T = \frac{\Delta Q}{C_V} \qquad (6)$$

Where: $T_{i,j,k}$ = is a temperature in time moment *t*, whereas $T'_{i,j,k}$ = is temperature in time moment *t* + *Dt*, C_V = specific heat conductivity of the given block. As far as this method is based on successive temperature calculation along coordinate axes, the stability condition must be respected: time pitch shall be followed by a pitch along axes:

$$\partial t \le (\frac{1}{2}k)(\frac{\lambda_{max}}{\vec{C}.\vec{l}})l_0; k = 1,2 \qquad (7)$$

Where: l_0 = distance between blocks. In 2D models this condition may be satisfied by calculation of heat transfer between blocks:

$$C\rho(\frac{\partial T}{\partial t} + \vec{V}\Delta T) = div(\lambda gradT) + F' \qquad (8)$$

Where: $\vec{V}$ = speed vector of heat transfer.

I have created such a model for the Merisi mining district. Thermophysical parameters necessary for calculations were published earlier (Tvalchrelidze, 2006). Figure 11 represents a block model of the geological environment at a depth of 2.5 kilometers before fault tectonics events and intrusion of the second phase took place. Figure 12 displays dynamics of crystallization and paleotemperature fields 122,000 years after the intrusion. Of course, paleotemperature fields were analyzed for different time periods, namely for: 6, 14, 22, 30, 46, 80, 122, 160, 180, and 250 thousand years after intrusion. However, the period of 122,000 years after intrusion has a decisive importance because by that time the massif was entirely crystallized (see Figure 12a). Such crystallization was followed by stabilization of the paleothermal field for a period from, at least, 122,000 – 250,000 years after intrusion.

The presented data allow formulation of several basic postulates discussed below.

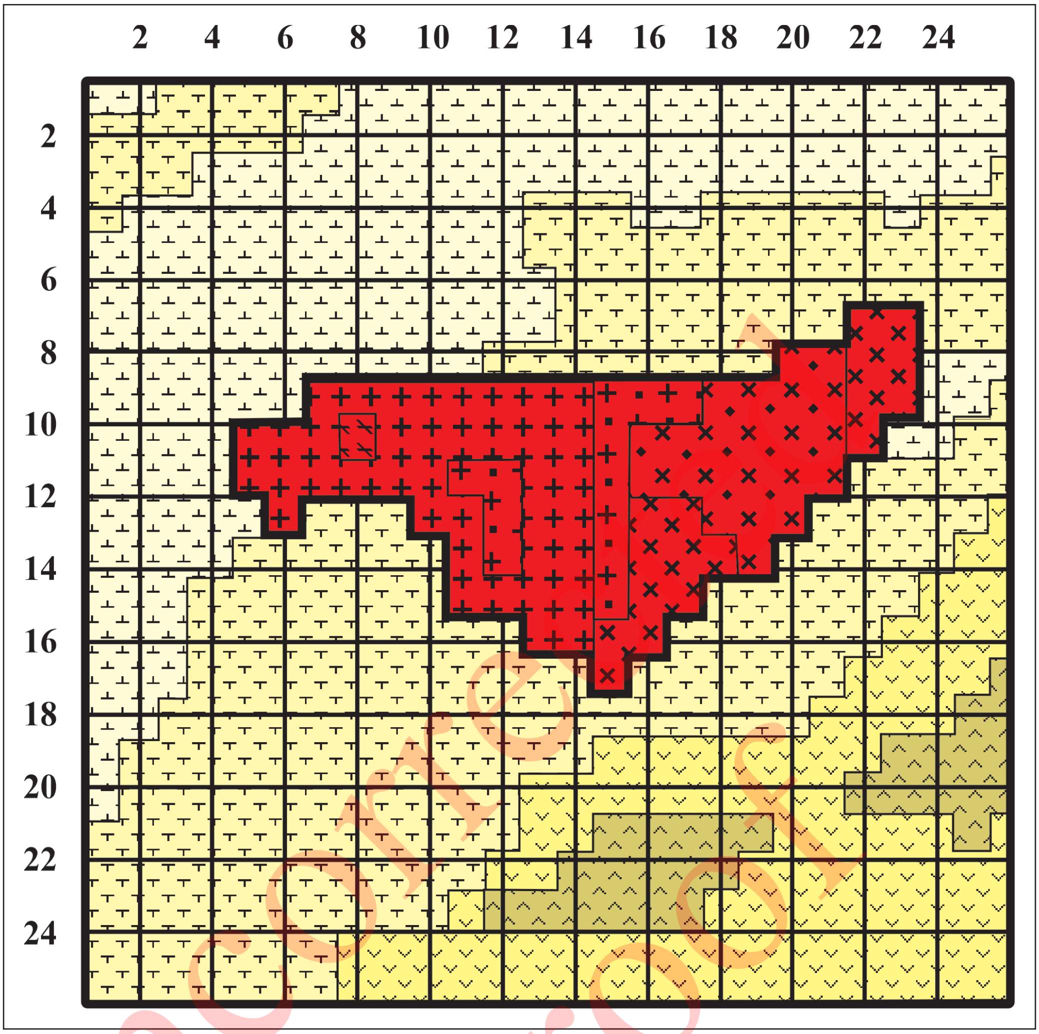

Figure 11 – Block model of the Merisi geological environment at a depth of 2.5 km immediately after intrusion of the main phase. Block numbers along coordinate axes are shown. Legend see on Figure 8.

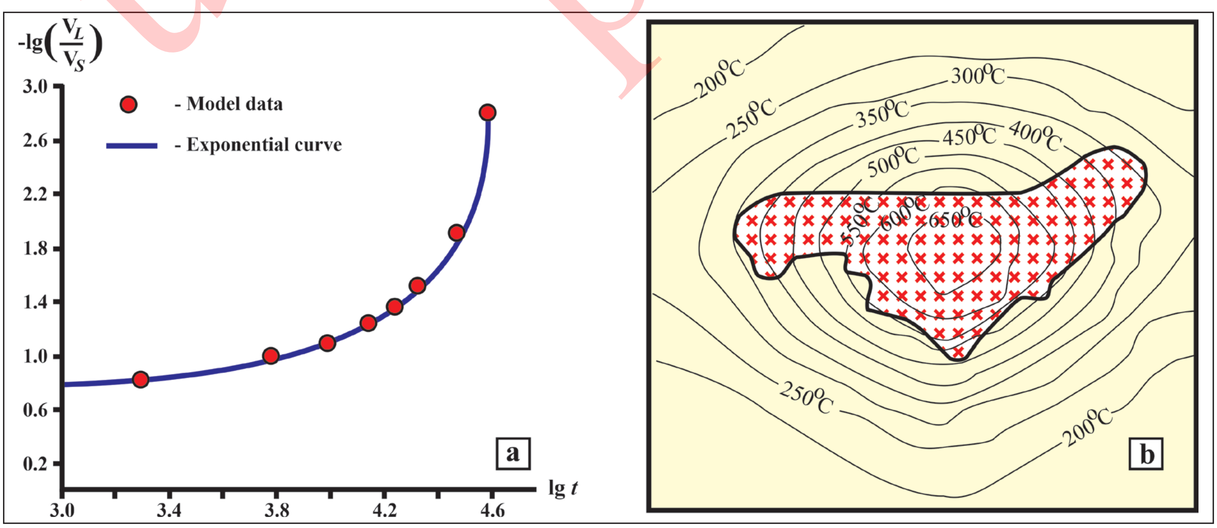

Figure 12 – Succession of crystallization, a) and paleotemperature field 122,000 years after intrusion, b) of the Merisi Pluton. V_L and V_S = correspondingly, volumes of the fusion and the crystalized phases; t = time in years.

5. Results

The classical thermodynamic approach, when formation of sulfide minerals is interpreted as reactions of mineral precipitation in equilibrium conditions, is unable to explain either creation of conventional flows of meteoric waters or ore formation of the analyzed type. For porphyry and epithermal ore formation some preconditions are suggested to exist:

1. Source of anomalous energy (heat), which exceeds normal thermodynamics of the enclosing environment.

2. Existence of temperature (and heat!) gradient, which determines conventional flows of fluids composed of endogenous and meteoric constituents (proven by rhythmical zoning of ore lodes).

3. Stability of such conditions for a period of sulfide ore formation – shorter this stability period is, smaller deposit is formed.

Such conditions may be created by different geological processes including heat transfer from a peripheric magmatic hearth considered in most epithermal deposit models. However, such models are not applicable for cases of complex ore-forming systems where porphyry and high and/or intermediate sulfidation ores are combined. In such cases heat necessary for ore formation is provided by a paleothermal field of cooling magmatic complexes. Such environment determines several fundamental features of these combined systems as follows:

1. In huge porphyry copper (± gold) deposits porphyry ores are located near the contacts (both endo- and exocontacts) of the intrusive massifs; only in small deposits they may occur in the central part of the igneous body. This phenomenon becomes quite understandable when paleothermal history of the cooling intrusive massifs is considered: As it is clear from Figure 12b, for the moment when the thermal fields were stabilized, temperature in the central part of the huge massif was too high for ore deposition.

2. The same reason determines absence of direct telescoping of porphyry ores into high sulfidation mineralization; it has been shown that between them exists a certain interval of ore-free ores, which corresponds to temperature decrease to a level appropriated for epithermal ore formation.

3. The cooling magmatic body is heating country rocks; with time, the paleotemperature gradient becomes smoother but the heated area – vaster. That is why between the first intermediate sulfidation deposit and the contact of the intrusive body a certain space does exist. Statistical analysis of numerous plutonogenic ore districts, performed by me earlier (see, for instance, Tvalchrelidze, 2006), has shown that this distance is pro rata dimensions of the magmatic body, and the correlation factor is very strong.

Hence, such a process of sulfide ore formation cannot explain formation of high sulfidation gold deposits. As it was explained, mass precipitation of free gold requires phreatic collapse in the ore conduit channel already after formation of hydrothermally altered rocks, and this event results in creation of either hydrothermal breccias, often with jigsaw-fit texture, or brecciated vuggy silica where host rocks and hydrothermally altered rocks are cemented by a gold-bearing quartz matrix.

The described model was proven by geological features of the deposits described in this article.

The model hereto allowed elaboration of a comprehensive exploration strategy and methodology, which lead to discovery of several porphyry copper and high sulfidation epithermal gold deposits. Four of them are intensively mined today, and mines at two other deposits are under construction. Several deposits are now successfully explored by our team.

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