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ORE-FORMING SYSTEMS IN VOLCANOGENIC-SEDIMENTARY SEQUENCES BY THE EXAMPLE OF BASE METAL DEPOSITS OF THE CAUCASUS AND EAST PONTIC METALLOTECT

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ABSTRACT.- By the example of Alpine volcanogenic base metal deposits of the central part of the Alpine-Himalayan fold belt (East Pontic Metallotect and Caucasus), it has been demonstrated that their hydrothermal systems naturally emerge at various stages of active interaction of microplates-continental fragments of Eurasia and Gondwanaland. During the divergence stage, at the microplates-boundary zones within the marginal sea, hydrothermal-sedimentary Cu and polymetallic deposits have been formed; at the early convergence stage, within the paleo-island-arc systems, epigenetic Cu and in lesser extent, barite-polymetallic (Lesser Caucasus), and later both combined (hydrothermal-sedimentary and stockwork) and epigenetic (mainly Cu- and Zn-containing) deposits have been originated (East Pontic Metallotect). In the beginning of collisional stage, in connection with antidrome volcanism within the back-arc volcanic structures, polyformational deposits (barite, barite-polymetallic, Cu, Au) have been formed. This tendency persists during the whole collisional stage - in the withinplate and transplate Eocene volcanic depressions - mainly polymetallic deposits have been originated in which the increasing contents of Ag take place in comparison to Au. The authors share the opinion that the primarily- anomalous environments for Cu-Zn deposits can have been "specialized" basic and medium-acidic volcanics whereas for baritic and barite polymetallic deposits gray colored and evaporitic sequences in the volcano-structure pedestals with buried highly mineralized brines seem to be most favorable.

Key words: Lesser Caucasus, Eastern Pontides, volcanogenic/sedimentary deposits, Murgul, Madneuli

INTRODUCTION

Volcanogenic deposits are typical of the active paleomargin of the Eurasian continent, more precisely, of its "fragments" - microplates (Scythian, Transcaucasian - Pontian) interacting with the passive Gondwanian paleomargin (represented by the Kırşehir, Taurus and Daralagez blocks). The continental blocks are separated from one another by suture zones most of which are marked by ultrabasic "melange" (Fig. 1). According to some authors (i.e. Vrielinck, 1994), the passive continental blocks drifted together with the oceanic plates. The mountain - fold belts contain the lithofacial information about changing geodynamic regimes under existing kinematics of lithospheric plates. Numerous publications (i.e. Monin and Zonenshain, 1987; Yılmaz et al., 1997; Okay and Şahintürk, 1977) indicate that among the main tectonic events conditioning the geologic framework of the Alpides are: 1- detachment of the Iranian microplate in Permian-Triassic time from Gondwanaland and its amalgamation to the active Eurasian margin; 2- opening Neotethys in Late Triassic-Early Jurassic (possibly its both branches) (Biju-Duval et al., 1977) in connection with the formation of rift systems; 3- obduction of oceanic complexes in Senonian marking the "death" of the ocean (Monin and Zonenshain, 1987).

The above events designate the principal stages of the historical - geological development in the Alpine cycle: first, divergence of microplates (Triassic-Early Bajocian) which caused the formation of the branches of Neotethys and activity of mantle diapirism; then, their convergence (Late Bajocian-Early Cretaceous) with especially island-arc andesitic volcanism at the margins and riftogenic volcanism in the central part of the Transcaucasian-Pontian microplate.

Maximum island-arc volcanic activity in the Transcaucasus took place in Bajocian - Late Jurassic while in the East Pontic metallotect - in Turonian - Santonian. Lately, on the basis of

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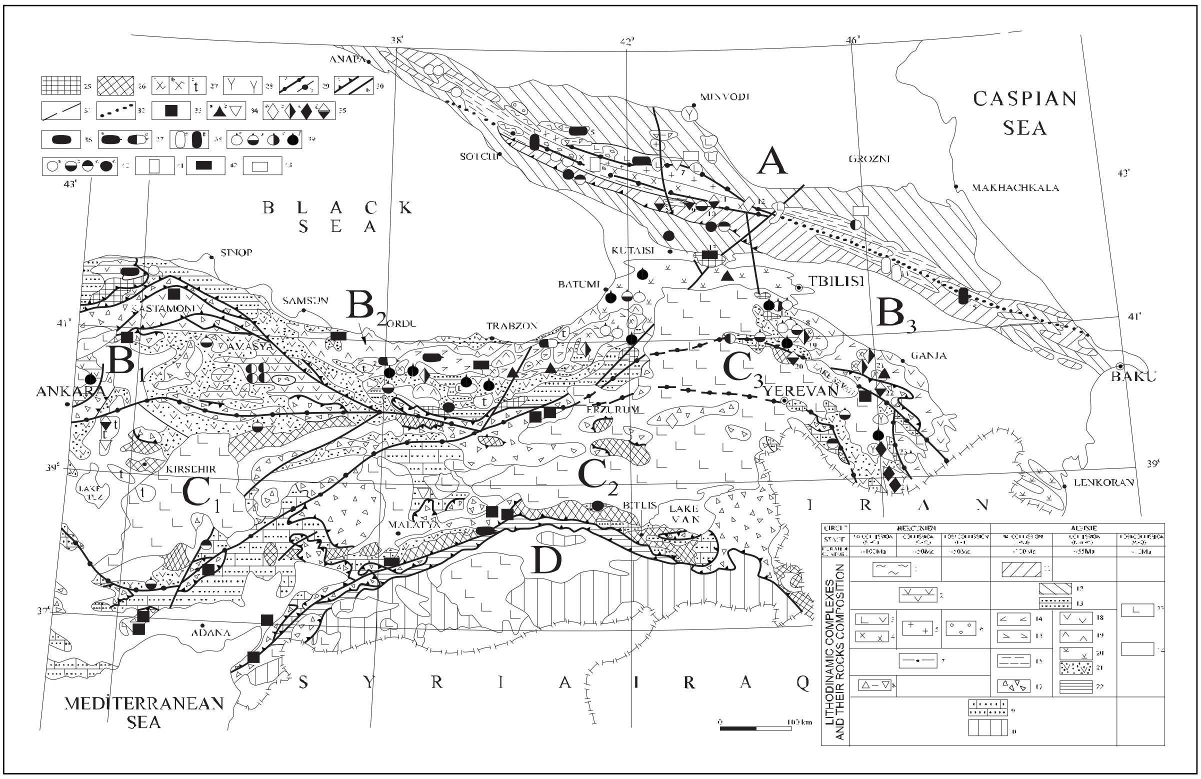

Fig. 1- Scheme of distribution of litho - geodynamic complexes and main types of metallic deposits of the central part of the Alpine-Himalayan belt (Eastern Turkey and the Caucasus), litho-geodynamic complexes; Hercynian: active margin of the East European paleocontinent: 1- Shelf and continental slope (Devonian-Carboniferous andesite-basalts, coaly-clay shales, limestones, greenstone alteration; Greater Caucasus); 2- Shelf zones of the continent (Carboniferous-Triassic sandstones, conglomerates, coaly shales, andesite-basalts; greenstone alteration; Pontides); 3- Ensimatic island arc (Devonian-Lower Carboniferous basalts, rhyolites, cherts, calcareous sandstones; Greater Caucasus); 4- Ensialic island arc (gabbro, granodiorites, parametamorphites of greenschist and amphibolite facies, blocks of pre-Cambrian schists; Greater Caucasus); 5- Uplifted activized blocks of ensialic arc (collisional granites, stavrolite and biotite-muscovite schists; Greater Caucasus); 6- Continental depressions (Permian- Triassic clays, sandstones, andesite-basalts, rhyolites; Greater Caucasus); 7- Paleo-marginal sea (Devonian-Triassic coaly-clayey shales, sandstones, andesite-basalts, olistostrome horizons, limestones; greenstone alteration; southern slope of Greater Caucasus); 8- Oceanic bed (calcareous and flint shales, basalts, peridotites, rhyolites in allochthonous occurrence; Greater Caucasus). Passive margin of Gondwanaland and later, since Mesozoic, of Afro-Arabian paleocontinent: 9- Shelf zones (Paleozoic- Cretaceous clays, sandstones, limestones, andesite-basalts, tuffites; Kırşehir, Taurus, Daralagez blocks); 10- Shelf zone of Arabian Block (Paleozoic-Eocene sandstones, clays, limestones, conglomerates). Alpine: active margins of the Eurasian paleocontinent: 11- Continental slope and rise of the Transcaucasian microcontinent (Jurassic-Lower Cretaceous andesite-basalts, trachyandesites, terrigenous - calcareous flysch, coaly-clay shales, granodiorites; southern slope of Greater Caucasus); 12- Shelf zones and slopes of the Scythian and Transcaucasian microcontinents (Jurassic-Paleogene andesites, andesite-basalts, shales, sandstones, multicoloured clays with sulphates, limestones and dolomites, marls, tuffites; Greater Caucasus); 13- Shelf zones and slope of the Pontian microcontinent (Lower Jurassic andesite-basalts, sandstones, limestones, shales; Late Jurassic- Cretaceous conglomerates, limestones, basalts, coral limestones, marls; Upper Cretaceous terrigenous-carbonaceous flysch; Pontides); 14- Lesser

Caucasian ensimatic island arc (Bajocian-Lower Cretaceous andesite-basalts, rhyodacites, tuffites, sand stones, shales, tonalites, diorites; southern margin of the Transcaucasian microcontinent); 15 - Pontian ensimatic island arc (Upper Cretaceous andesite-basalts, rhyodacites, marls, sandstones, shales); 16- Troughs within the marginal paleo-sea (Lower and Middle Jurassic shales, basalts, rhyolites, gabbro-diabases; Greater Caucasus); 17- Oceanic zones in allochthonous occurrence (in the form of sutural and obducted deformed slabs - ultrabasic "melange", harzburgites, serpentinites, gabbro, tholeiites, alkaline basalts, flysch with ophioclastic olistostromes, radiolarites; Pontides, Taurides, Lesser Caucasus); 18- Residual Lesser Caucasian back-arc paleodepressions (Senonian-Danian andesites, rhyodacitic ignimbrites, rhyolites, trachyrhyolites, limestones, basalts, granodiorites); 19- Residual Pontian back-arc paleodepressions (Campanian-Danian basalts, rhyodacites, trachyrhyolites, coral limestones); 20- Intraplate superimposed riftogenic depressions (trachyandesites, trachybasalts, volcano-terrigenous flysch with olistostromes, gabbro-diorites, monzonites, syenites, alkaline gabbroids and syenites); 21-Superimposed marine volcanodepressions (Eocene andesites, trachyandesites, terrigenous-carbonaceous flysch, sandstones, shales); 22- Flysch troughs (south margin of the Taurus carbonate platform) emerging as a result of collision of the Taurus with Eurasia (Senon-Eocene-Oligocene sandstones, marls, shales, ultrabasic fragments); 23-Volcanic plateau-activated blocks of fold systems (Neogene-Quaternary andesites, andesite-basalts, basalts and their pyroclastics); 24- Intramontane depressions and foredeeps of fold sysems (Oligocene-Quaternary marine and continental molasse); 25- Crystalline basement of the Eurasian continent (pre-Cambrian-Early Paleozoic); 26 - Crystalline basement of Afro-Arabian continent (pre-Cambrian?); 27- Granitoids (pre-collisional: a - Lower Cretaceous, b - Upper Cretaceous, c - Eocene-Oligocene collisional); 28- Post-collisional monzonites, syenites, granodiorites; 29- Suture zones (a - reliable, b - presumable beneath the younger sediments); 30 - Faults (a - thrusts and reverse faults, b -sub-vertical faults); 31- Caucasian lineaments interpreted from space photographs; 32- Presumable boundary between Scythian and Transcaucasian microplates. Genetic types of deposits: 33- Magmatogenic (chrome minerals); 34- Skarn (a- iron-ore, b- tungsten-molybdenum); 35- Hydrothermal-plutogenic (a- polymetallic, b- copper-porphyry, c-copper-molybdenum-porphyry, d- gold-bearing); 36- Hydrothermal-sedimentary in volcanic rocks (copper with zinc); 37- Combined hydrothermal-sedimentary and stock work in volcanic rocks (a - copper, b - copper-zinc); 38- Hydrothermal-sedimentary in shales (a - polymetallic, b - copper metamorphogenic); 39- Hydrothermal-volcanogenic epigenic (a - copper, b - polymetallic with barite, c - polyformational: copper, barite, barite-polymetallic, gold-bearing in secondary quartzites, d - gold-bearing); 40- Hydrothermal "amagmatogenic"-telethermal (a - mercury, b - arsenic-realgar-orpiment with gold, c- lead-zinc , d- barite); 41- Hydrothermal-metamorphogenic (tungsten); 42- Sedimentary and volcanogenic-sedimentary (?) (manganese); 43- Sedimentary (celestine). Main deposits of the Eurasian active paleomargin:1- Aşıköy (Cu); 2- Lahanos (Cu, Zn, Pb); 3- Çayeli-Madenköy (Cu, Zn); 4- Murgul (Cu, Zn); 5- Urup (Cu); 6- Kty-Teberda (W); 7- Thir-Nyauz (W); 8- Lukhra (Au); 9- Tcana (As, Au); 10- Lukhumi (As); 11- Zophito (Au, Sb); 12- Sadon (Pb, Zn); 13- Chiatura (Mn); 14- Filizchai (Zn,Pb, Cu); 15- Kızıldere (Cu); 16- Madneuli (Cu, Pb, Zn, Ba, Au); 17-Alaverdi (Cu); 18- Chamlug (Cu); 19- Tekhut (Cu); 20- Megradzor (Au); 21- Dashkesan (Fe, Co); 22- Zoti (Au); 23- Kafan (Cu); 24- Kadjaran (Mo, Cu). The paleomargin of the Eurasian continent active during the Alpine cycle: microplates: A- Scythian, B- Pontian-Transcaucasian (B1- Western Pontides, B2- Eastern Pontides, B3- Transcaucasia). Passive paleomargins of the Afro-Arabian continent: microplates: C1- Kırşehir, C2- Taurus, C3- Daralagez (North Iranian). Microplates are divided by suture zones. D - Arabian projection (boundary with the Taurus is marked by system of thrusts). The western part of the scheme is compilied on the base of maps published by MTA (Turkey): geological, on a scale 1:500 000 (1961) and 1:2 000 000 (1989); metallogenic, on a scale 1:2 500 000 (1977) and 1:1 000 000 (2000). Besides, it has been used an unpublished map of the Eastern Pontides on a scale 1:250 000.

comparative structural-facial analysis, Yılmaz et al. (2000) have convincingly shown the differences in the geodynamic evolution of individual segments of the Transcaucasius - Pontian microplate. The beginning of the collision was different in time in western and eastern parts - joining the Transcaucasia and Daralagez block took place in Coniacian (Monin and Zonenshain, 1987) whereas the East Pontic metallotect was amalgamated with the carbonate platforms somewhat later - in Campanian (Dixon and Pereira, 1974).

During the collisional stage in Late Cretaceous-Eocene, volcanic activity first appeared in the residual back-arc basins and, later, in depressions superimposed on older tectonic structures in Eocene volcanics. The process of collision was accompanied by intensive reorganization of earlier geomorphological structures. The overthrusting of oceanic flyschoid series on adjacent continental blocks and obduction of oceanic crust were marked by diverse forms of volcanic activity-parallel with andesitic volcanism there appeared subalkaline and alkaline volcanics; besides, some crustal magmatic sources were activated as well.

The process of disruption of macrostructures - destruction in the north connected with the formation of Paratethys followed by intensive emergene of mountain-fold systems-continued during the whole postcollisional stage which remains beyond our study as bearing no relation to the genesis of base metal deposits.

The scheme shows that volcanogenic deposits are associated with geodynamic complexes formed in the following situations:

1- Depressions of marginal seas (hydrothermal-sedimentary Cu and pyrite-polymetallic mineralization of the divergent stage, Cu in Dagestan and Turkey, polymetallic in Azerbaidjan);

2- Intra-arc marine basins of different age (hydrothermal-sedimentary and epigenetic Cu and Cu-Zn deposits of the East Pontic metallotect and the Lesser Caucasus. Within the uplifted blocks there are Au-polymetallic deposits as well - Shaumian in Armenia and Cerattepe in Turkey);

3- Residual back-arc Cretaceous volcanostructures (epigenetic near-surface Cu, barite, barite-polymetallic and Au-bearing deposits of the Bolnisi district in Georgia);

4- Withinplate and transplate collisional Eocene volcanic depressions (epigenetic polymetallic, with silver and Au, and barite deposits of Georgia, Armenia and Turkey).

The most significant deposits are concentrated within the first three types of volca-nostructures.

VOLCANOGENIC DEPOSITS

Hydrotheral-sedimentary deposits of the divergent stage have been discovered in the east in shales of the Greater Caucasus, and in the western part of the Pontides, in the volcano-sedimentary Küre complex. Ore bodies are within allochthonous slabs, some of which are intensively deformed; primary mineralization has sometimes been subjected to metamorphism as in case of the Kızıldere deposit in Dagestan.

The Cu-pyrrhotite Kızıldere deposit is located at the junction of the Scythian and Transcaucasian microplates in the paleo-depression of the marginal sea strongly deformed by subsequent tectonic stresses. Lower Jurassic shales together with syngenetic pyrite deposits were deformed into a series of complicated folds. Shales, at some distance from the deposit, contain greenstone-altered tholeiitic basalts and medium-asidic intrusions (Borodaevskaya, 1979; Bogdanov et al., 1983). The pyritic bodies forming two large lenses are related to a synclinal fold; they are composed of syngenetic pyritic and epigenetic Zn-pyritic and younger Cu-pyrrhotite ores.

The Filizçay pyrite-polymetallic deposit forms a single large ore body (Bogdanova et al., 1983) situated at the boundary between the shales and overlying flyschoids. A sheet ore deposit of syngenetic ores is made up of individual pyrite-carbonate, sphalerite-galena, chalcopyrite-pyrite and clayey "rhythms". In the flanks of the deposit, ore "flysch" is developed and underlain by shales bearing veinlet-impregnated mineralization. Characteristic features of the enclosing shales near the deposit are pyritic concretions and, at some distance, sideritic. In the eastern part of the deposit coarse-grained spotted pyrite-sphalerite-galena ores derived from the recrystallization of the primary ores are developed. The impregnation ores in the hanging wall are dissected by vein-shaped Cu-pyrrhotite mineralization. At some distance from the submarine depressions with stagnant water where hydrothermal fluids discharged, local volcanic centers of basalt-andesite-dacite eruption were situated. It may be assumed that in case of the Filizçay deposit, the substratum of ore-bearing formation could have been rigid sialic blocks whereas the Cu-pyrrhotite ores Kızıldere-type were originated in the axial zones of riftogenic structures characterized by tholeiitic basalt volcanism.

One of the examples of divergent deposits is Aşıköy located within the allochthonous Küre complex of the Pontides (Fig. 2). Some researchers (i.e. Ustaömer and Robertson, 1993) attribute the Küre complex composed of Triassic-Lower Jurassic volcano-sedimentary sequences to south-vergent accretionary structure squeezed from the marginal basin of Paleotethys. According to the above mentioned authors, the Küre complex demonstrates the standard succession of rock units characteristic of the axial parts of rifts: serpentinous peridotites, cumulate and isotrope gabbro, diabase dyke complex, greenstone-altered tholeiitic pillow basalts. The latter are overlain by shales the contact zone of which contains Cu-bearing pyrite deposits similar to those in Cyprus (Güner, 1980). In the Aşıköy quarry (Fig. 3), the following complicated pattern of rock relationship can be observed: serpentinized peridotites are overthrust the basalt-clay-shale complex; the complex itself is overturned to the south with pillow lava overthrusting the shales; the latter contain a body of fine-grained pyritic ores. The basaltic flows are marked by the presence of tectonites within which fragments of rocks, and the pyritic ores are cemented by coarse-grained chalcopyrite-pyrrhotite matrix.

Volcanic rocks developed within island arc systems are characterized by the presence of both hydrothermal-sedimentary and epigenetic ores. In the East Pontic metallotect, the ore deposits are related mainly to Santonian dacites and their pyroclasts.

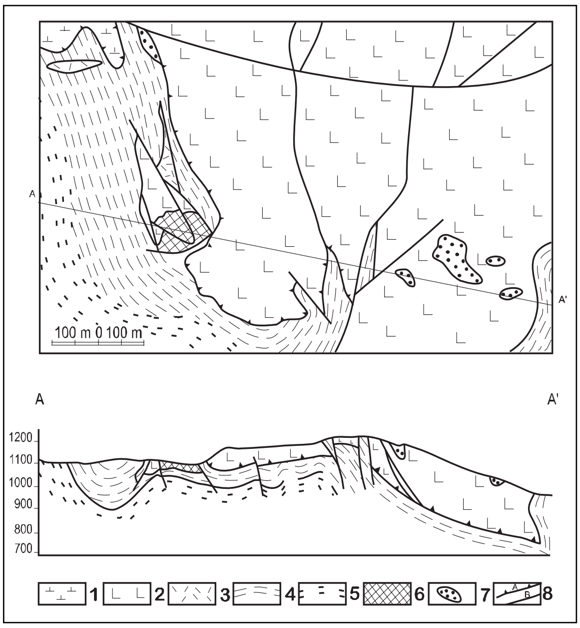

Fig. 2- Geological map of the Aşıköy deposit. 1- ultra basics (allochthonous); 2- greenschis basaltes; 3- dacites; 4- sholes with rare sandstones; 5- alternation of sandstones and shales; 6- massive pyrite chalkopyrite ores; 7- iron hat; 8- faults: a- thrusts, b- subvertical.

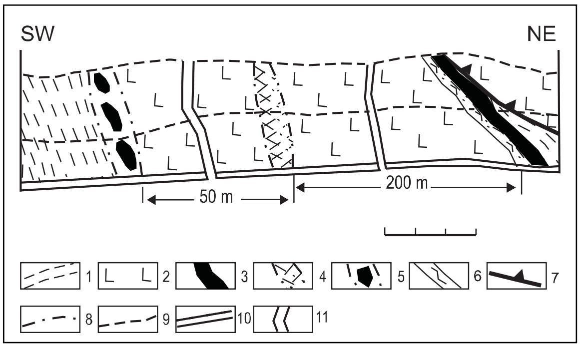

Fig. 3- Sketch-map of western part of the Aşıköy quarry.

In the Madenköy deposit, massive-bedded brecciated pyrite-sphalerite-chalcopyrite ores form a large body overlain by silicified and ferruginated tuffites. The underlying dacites show veinlet-impregnated mineralization. The overlying sequence is composed of interbedding tuffs, tuffites and basalt flows.

The deposit is quite significant by its dimentions: about 900 m along the strike, 600 m along the dip, and up to 100 m thick. The upper horizons of the deposit, which reveals a certain similarity to Kuroko, contain polymetallic brecciated ores composing of pyrite, chalcopyrite, sphalerite, and small amounts of galena, bornite and sulphosalts. The vein varieties are represented by barite, dolomite, quartz, sericite and kaolinite. The clastic ores are underlain by massive black sphalerite, with admixture of chalcopyrite and yellow pyrite-chalcopyrite ores; besides, some types of brecciated ores are also present.

The best examples of stockwork deposits in the East Pontic metallotect are Lahanos and Murgul. In Lahanos, the stockwork of sphaleritepyrite-chalcopyrite composition is within the dacitic stock. Veinlet-impregnated mineralization is concentrated within the quartz-sericite-chlorite metasomatite areal. According to Özgür (1993), the deposits of Lahanos and Madenköy are of Kuroko-type deposits.

The resembling geological position is occupied by the Murgul deposit (Fig. 4). The stockwork of pyrite-chalcopyrite ores is limited at the top by quartz-ferruginous (jasper-like) sediments with gypsum lenses. Ore-bearing dacitic lavas are eroded and unconformably overlapped by Campanian-Maastrichtian volcanites. The Murgul deposit might be interpreted as a transitional type tending to porphyry Cu deposits (Özgür, 1993).

The deposits of pre-collisional stage in the Lesser Caucasus are represented by epigenetic ore bodies (Fig. 5) formed in Late Bajocian-Bathonian (Alaverdi, Kafan) and in Late Jurassic (Shamlug).

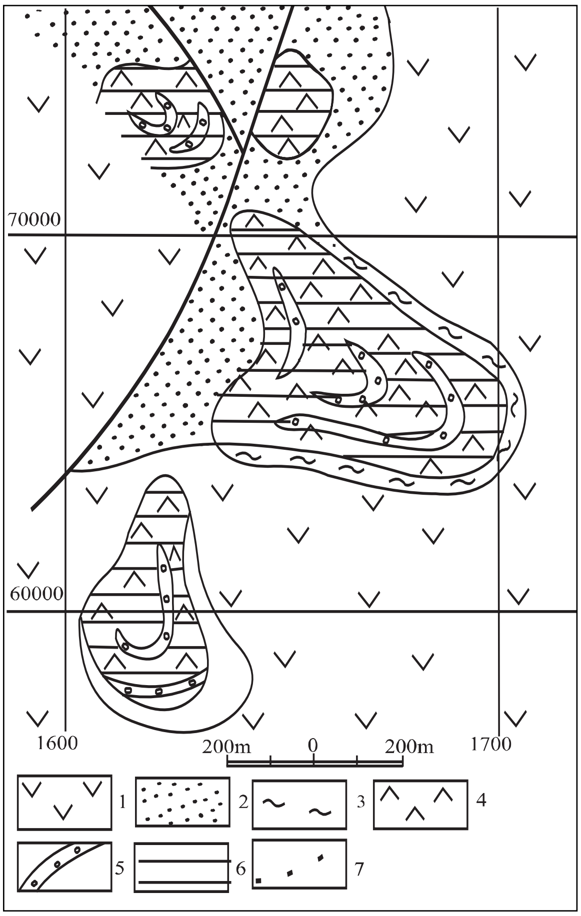

Fig. 4- Geological sketch-map of the Murgul deposit. Late Senonian (Campanian-Maastrichtian) rocks: 1- Andesites and dacites; 2- argillites, sandstones, tuffites (overlie mineralization); Early Senonian (Santonian) ore-bearing rocks: 3- siliceous-iron sediments; 4- dacite lavas and their pyroclastolites (within the mineralized, blocks) - breccias and quartz-sericit-chlorite metasomatites; 5- gypsum lenses; 6- shtock work pyrite-chalcopyrite sphalerite ores; 7- faults.

In the Alaverdi ore knot, the ores are concentrated in the andesite-dacite Bajocian unit overlain by volcano-sedimentary rocks of Callovian age. In Alaverdi, the Cu ores (lenses, stockworks and veins) are concentrated beneath the cover of Late Bajocian sedimentary rocks; in Shamlug, Callovian rhyodacites serve as screen for ore bodies; in Akhtala, barite-polymetallic mineralization does not overstep the limits of the rhyodacitic stockwork. In Kafan, the distribution of the stockwork and Cu ore veins is controlled by a subvolcanic dacitic volcanism. Here, ore-bearing rocks are overlain by tuff-sandstones with lenses of gypsum and pyritic impregnation. The flows of unaltered andesitic lavas rest on the top of ore-bearing rocks. In all the deposits, the mineralization is accompanied by quartz-sericite metasomatites locally revealed against the background of areal propilites.

In the Bolnisi district of Georgia, the volcano-tectonic depression is filled with andesite-dacite lava-pyroclastic material and shallow-marine terrigenous sediments of Turonian-Early Santonian age and Late Santonian rhyodacitic lavas and ignimbrites. The lower volcano-sedimentary sequence is composed of K-Na granodiorite porphyry and quartz diorite.

Within the exploited Madneuli deposit (Fig. 6) localized on the slope of a large volcanic edifice under the screen of rhyodacitic extrusions and ignimbrites, there have been identified spatially disconnected Cu, barite-polymetallic, barite and Au (in secondary quartzites) ores. Ore-bearing clastic tuffites have been subjected to very intensive explosive brecciation and transformation. The upper levels of the secondary quartzites contain barite and barite-polymetallic gently sloping ore bodies and veins; the lower horizons composed mainly of quartz-sericite-chlorite metasomatites enclose pyrite-chalcopyrite stockworks and veins.

The boundary between the quartzite-breccias and quartz-sericite metasomatites coincides with a tectonic zone, locally with traces of ferrugination and gypsum mineralization. The same level reveals lens-shaped pyrite concentrations with small amount of chalcopyrite and sphalerite. At the depth, the Cu stockwork is replaced, along narrow zones, by poor chalcopyrite-pyrite-Mo impregnation accompanying by anhydrites. The latter are observed in quartz diorites, at a depth of 900 m from the surface. The secondary quartzites are dissected by blueish chalcedony-like quartz with Au.

The authors of this paper dispose data on isotopic composition of strontium and concentrations of rubidium and strontium in rocks located near volcanogenic and possibly having paragenetic bonding with latter (see table I, sample MR is produced by R. Migineishvili).

It is considered, that isotopic correlations of elements with high mass number remain invariable in magmatic processes of evolution and correspond to isotopic composition of primary source of rocks (Balashov, 1985; Abramovitch et al., 1989). From the table 1, it is seen, that basalts, monzonites, gabbro-monzonites and dacites represent "differentiation" products of depleted mantle. In basic rocks melted from depleted mantle, rations between strontium isotopes is equal to 0.7045, while the magma source of lamprophyres and rhyolites could arise in the earth's crust.

Recently published paper (Gugushvili et al., 2002) contain data on rare-earth elements and other rare-elements concentrations in volcanic rocks of Bolnisi district of Georgia. On uppercrustal source of rhyolite and ignimbrite magmas of Madneuli deposit testify determined rations of Eu (for rhyolites - Eu/Eu*= 0.65-0.68, for ignimbrites - Eu/Eu*=0.52-0.58) and indicates characteristic enrichment by light rare-earth elements and large-ion lithophilic elements (K, Rb, Ba, Sr). In dacites and andesite-basalts enrichment by light rare-earth elements were manifested as well. Eu/Eu* ratios turned out to be 0.72-0.77 and 0.72-0.81. Characteristic feature of basalts is enrichment by Eu (Eu/Eu* = 1.01-1.07). Gugushvili et al. (2002) infer on various levels of formation of magma for rocks of volcanic structure in Bolnisi district for uppercrustal rhyolites and ignimbrites, lowercrust for dacites and andesite-basalts and mantle for subalkaline basalts.

According to geological observations-"antidromous" character of volcanisms at the collision stage, at the beginning crustal sources of magma are activated and later on the mantle ones as well. Despite the different ways of ore-formation (hydrothermal-sedimentary and epigenetic), volcanogenic deposits are characterized by a number of common features. Their hydrosystems are functioning in volcano-depressions whose basements are complicated by intrusions. The roots of the latter in the present-day active zones of oceans (Greenberg et al., 1990) are located at a depth of 1-2 km beneath the sea floor; in epigenetic deposits (e.g. in the Bolnisi district) they are at a depth of 1-1,5 km beneath the paleo-surface (according to borehole data). The componental composition of deposits is essen-

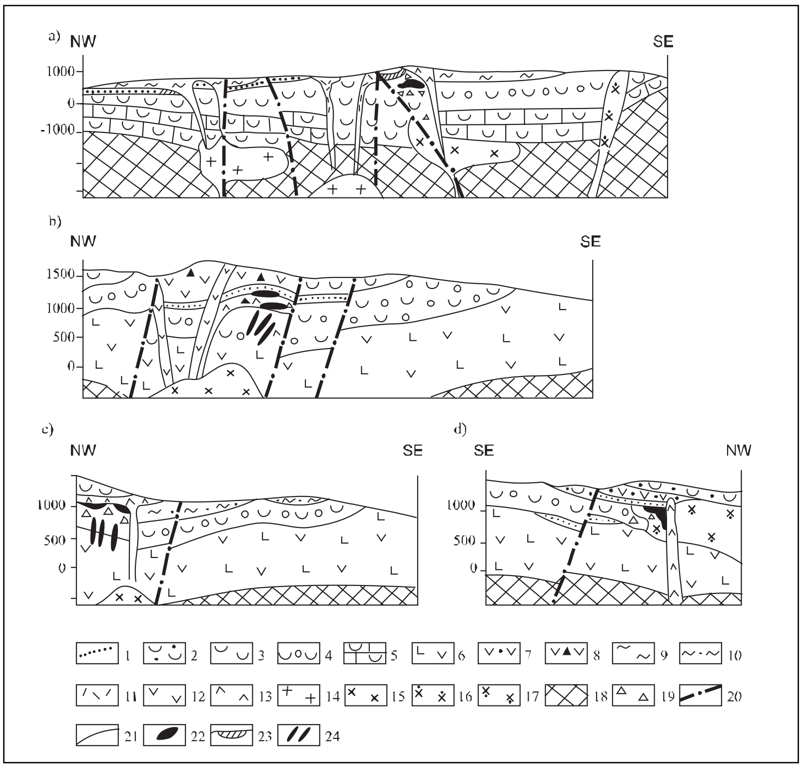

Fig. 5- Fragments of ore-bearing volcanic structures of the Lesser Caucasian island paleoarc. Fragments of: a- Late Cretaceous backarc residual depression (deposits: complex barite, barite and polymetallic and Cu- Madneuli and David Garedji); b, c, d- the Baiosian-Late Jurassic intraarc depression (b- Bathonian Cu Alaverdi deposit, c- Late Jurassic Cu Shaming deposit, d- the Middle Jurassic Cu Kaphan deposit). 1- carbonate-terrigenous sediments (thin horizons); 2- terrigenous-volcanogene rocks (Late Jurassic volcanogene flysh); 3- psammo-psefitic tyffites, andesite-dacite horizons [Late Cretaceous (a) and Middle Jurassic (b, c, d)]; 5- tuffites, limestones, sandstones, andesite, andesite-dacite, andesite-basalt lavas (Lower Cretaceous complex of the Bolnisi depression); 6- lavas and lava breccias of andesite-basalts and basalts, tuffites (the Early Bajocian); 7- andesite lavas (Middle Jurassic); 8- lavas and lava breccias of andesites, andesite-basalts (Middle Jurassic-Bathonian); 9- ignimbrites (Late Cretaceous); 10-hyaloclastics (Middle Jurassic); 11- K-Na rhyolites (Late Cretaceous); 12- andesite-dacites (Middle Jurassic); 13- dacites and rhyodacites (a- Late Cretaceous, c- Late Jurassic, b,d- Middle Jurassic); 14- K-Na grano-diorites and granites (Late Cretaceous); 15- Na granodiorites (Late Cretaceous, Late Jurassic and Middle Jurassic); 16- quartz diorites (Late Cretaceous); 17- quartz diorite porphyries (Middle Jurassic); 18- Pre-Mezozoic basement; 19- explosive breccias; 20- faults; 21- conditional margins of geological bodies; 22- stock-like Cu orebodies; 23- barite lodes; 24- Cu vein bodies.

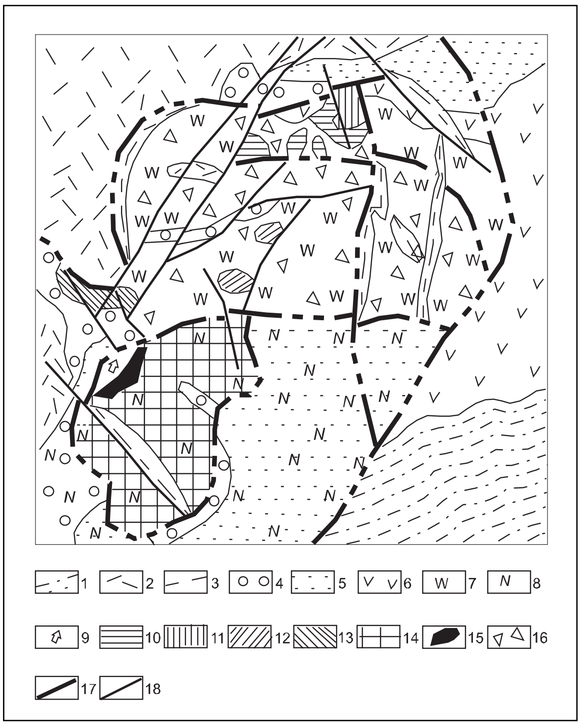

Fig. 6- Geological and structural map of the Madneuli open pit mine. 1- extrusive rhyodacites; 2- rhyolite lavas; 3- subvolcanic rhyolite bodies; 4- vortoclastic tuffs; 5- psammo-psephite and alevrolitic tuffs; 6- aglomerate and psammo-psephitic xenotuffs; 7- secondary quartites; 8- quartz-sericite-chlorite metasomatics; 9- gypsum and anhydrite accumulations; ores: 10- barite; 11- massive barite-Pb-Zn; 12- veinlet polymetallic; 13- veinlet Cu-Zn; 14- veinlet and impregnation Cu; 15- base metal massive sulphide; 16- explosive breccia; 17-gentle faults; 18- subvertical faults.

tially influenced by geological environment. In the present-day rift zones and in older structures, Cu-pyrite-Zn deposits overlie directly the Cyprus-type basalts. At the same time, in the presence of thick sedimentary layer with evaporites, as in the Gorda ridge (Koski et al., 1985), the ores turn into polymetallic. The generally-accepted genetic model (Franklin et al., 1984; Krivtsov, 1989) implying extraction of metals by overheated sea waters encounters some difficulties in explaining the mechanism of accumulation of huge masses of polymetallic ores (Filizçay) or barite (Madneuli). The authors are rather inclined to share the idea that the source of barite-polymetallic deposits may be the high-mineralized chloride brines buried in evaporitic fillings of volcanic depressions. In the Caucasus, as in the other parts of the Mediterranean belt, geodynamic (shallowing Paleothetys at the end of the Hercynian cycle) and climatic conditions of the Triassic time do not exclude the possibility of formation, within vast shelf areas, of residual terrigenous salt-bearing gray-coloured rock units with buried brines, such as now observed throughout the globe (Lebedev, 1975; Weisberg et al., 1982; Goleva, 1993; Kislijakov and Shchetochkin, 2000).

Cu-bearing hydrothermal-sedimentary deposits are dominated by massive pyritic concentrations enriched in Cu and Zn. The deposits, in most cases, are overlain by microquartzites or siliceous-hematite jaspers. At this level and sometimes on the flanks between stockworks and bedded ore bodies of Kuroko type (Matsukama and Khorikosi, 1973) gypsum concentrations are also observed. The epigenetic deposits (Madneuli, Kafan, Murgul) are not the exceptions to the rule. Here also, above the stockwork ores there are zones of jasper-like quartzites and not very large lenses of gypsum and pyrite.

Microrhythms in the Filizçay polymetallic deposit reveal a certain similarity to the mineral zonality observed in the epigenetic deposits (Madneuli). Barite-polymetallic coarse-grained massive aggregates in Madneuli are downward replaced by veinlet mineralization; in the lower horizons, the replacement of the galena-sphalerite association by the sphalerite-pyrite (with Cu) one takes place. Very impressive is also the resemblance of the barite-polymetallic part of the Madneuli deposit with the Kuroko-type deposits (Matsukama and Khorikosi, 1973).

The PT conditions of ore accumulation were similar within the epigenetic and hydrothermal-sedimentary deposits. In epigenetic, as well as in some hydrothermal-sedimentary deposits, the process of boiling - the solution with precipitation of ore material in the form of gel - was followed by a period of slow emission of the solution and

Table 1- Isotopic analysis of stroncium and definition of rubidium and strontium concentration by the method of isotopic dilution was carried out by the Institute of Pre-Cambrian Geology and Geochemistry of Russian Academy of Sciences.

Number of samples	Location	Rocks	Rb ppm	Sr ppm	$^{87}Rb / ^{86}Sr$	$^{87}Sr / ^{86}Sr$	+/- 26
8	Bolnisi District Georgia	Basalt	9,82	538	0,0506	0,704910	23
19	Merisi Ore region Ajara, Georgia	Monzonite	96,9	507	0,5523	0,704606	18
20	Same location	Gabbro-monzonite	63,1	700	0,2608	0,704766	17
21	Same location	Lamprophyre	76,9	542	0,4106	0,705361	15
22	Bolnisi District Georgia	Dasite	19,8	399	0,1436	0,704563	18
32	Same location	Rhyolite	19,3	28,7	1,943	0,710269	16
MR	Murgul Deposit, Turkey	Rhyodasite	64,5	94,7	1,971	0,707739	19

crystallization of mineral masses. As a rule, the level of boiling at the temperature of more than 270°C in regions of recent volcanic activity is located at the depth of 300-400 m from the present-day surface (Sinyakov, 1986). As for the "quiet" period of ore-accumulation in the epigenetic deposits, its PT conditions (Kekelia et al., 1993) were corresponding to the pressure of about 20 MPa and the following temperatures: 370°-260°C for Cu ores, and 280°-180°C for barite-polymetallic ones. The baritic deposits were formed under low temperature (~ 100°C) and pressure (~ 5MPa). In Filizçay, the pyrite ores were ennobled by mineralization of the second polymetallic phase, within temperature range between 250-100°C; the following superimposed Cu-pyrrhotite association was formed under 370-400°C (Bogdanova et.al., 1983). It is also noteworthy that the most favourable PT-conditions for the stable accumulation of hydrothermal-sedimentary deposits were created at the bottom of sea basins with a depth of about 2 km (Stackelberg, 1985).

"Ore" hills can rise at the even greater depths, up to 3000 m (Gablina et al., 2000). The shallower portions of the sea-floor also are not restricted for ore-accumulation, especially for barite and barite-polymetallic ores, but they are not favourable for the stable course of the process owing to the upwelling and rough conditions of shelf zones. Within the pre-collisional depressions (irrespective of the way of ore-accumulation) the hydrothermal activity had mainly single-phase character while in the collisional volcanostructures this process was multiphase due to the discontinuous and antidrome manifestation of volcanism.

It has been already mentioned the resemblance between the Madneuli and some Miocene Japanese deposits (the presence of isolated barite bodies and barite-polymetallic mineralization, including gypsum in the lower horizons). The main difference, however, is that in Madneuli the process of ore-accumulation was realized within the closed volcanostructure whose final formation took place in submarine situation. The earlier model (Kekelia et al., 1991) assumed the participation of buried bedded sea waters in ore-accumulation some of them might have primarily been ore-bearing (brines); the others, occuping higher horizons at a considerable distance from the volcanostructure, were involved in the process of ore-formation in the later stage and metamorphosed, and acquired the ability for extraction of ore components.

During the first stage, squeezing rhyolitic extrusions along the ring structures on the slope of the volcano resulted in the formation of a closed dome-shaped ore-bearing structure; then, heated and saturated with volatile magmatic components, bedded waters were "sucked in" and subjected to collapse at a depth of 400-500 m from the surface. As a result, explosive breccias were formed, mainly at the expense of tuffites and effusive rocks, beneath the impermeable screen. Under the action of hydrothermal activity, they underwent pre-ore transformations with segregation of two paleohydrochemical zones: the upper one - sulphate-ammonium (the level of secondary quartzites), and the lower one-chlorite-sodium (quartz-sericite-chlorite metasomatites); the boundary between the zones is traced by jasper-like quartzites and gypsum concentrations. The creation of pre-ore situation was facilitated by:

1- Boiling of the solution and its alkalization due to separation of acidic components and precipitation of sulphides, native metals (Au), quartz, carbonate, adular;

2- Oxidation of H_2S, HCl, CO_2, NH_4 in the higher levels;

3- Exchanging reactions with the surroundings possessing buffered properties.

Barite and barite-polymetallic ore-formation (ores superimposed on disintegrated secondary quartzites) proceeded against the background of the earlier paleohydrochemical situation with synchronous accumulation of sulphates and sulphides in the boundary zone. Beneath the latter, in traps saturated with hydrogene sulphide, pyrite ore bodies of limited dimentions have been concentrated.

The later Cu veinlet-impregnated ores are considered to be the products of an independent ore-formation stage. They were formed under new tectonic dislocations imposed on the volcanostructure and injection of a quartzdiorite intrusion.

For both epigenetic Cu and hydrothermal-sedimentary Cu-Zn pyrite deposits, the most logical is the convective model. The model assumes that metals were transported in the form of hydrosulphide complexes and precipitated, according to the generally accepted opinion, as a result of falling in temperature and oxidation of the solution.

The formation of volcanogenic-sedimentary polymetallic (with barite) ores proceeded in a different way. The solutions involving in the hydrothermal system are practically devoid of H_2S-containing components (Lebedev, 1975; Weissberg et al., 1982; Kraynov et al., 1988). Lebedev (1975) carried out an experiment mixing metal-containing brines with H_2S-containing waters obtained from various levels of above-hole drilled in the Cheleken peninsula (Turkmenistan). As a result of the mixing, the precipitation of sulphides of Pb and Zn took place. It is noteworthy that the Cheleken brines are very similar in temperature and salinity to the brines of the Red Sea (Degens and Ross, 1974).

The above material allows to speak of the specific conditions of the discharge zones, namely brine outflow was preceded by accumulation of H_2S- containing oozes in the sea depressions. The enrichment of the oozes with hydrogen sulphide can be realized:

1- As a result of biogenic reduction of sulphate in sea water;

2- At the expense of hydrogen sulphide derived from deeper katagenic zones where it is generated by abiogenic ways;

3- As a result of degassing shallow-occurring magmatic source. Taking into consideration data on isotopic ratio of sulphur in sulphides (Bogdanova et al., 1983) we give preference to the third way. Precipetation of ore material in mass volumes is, most likely, a result of mixing H_2S-containing waters with outflowing brines.

DISCUSSION

Most researchers hold the opinion that the hydrosystems of volcanogenic deposits developed according to the convective model implying involvement of exogenic waters in the hydrothermal process (Franklin et al., 1984; Ovchinnikov, 1988; Krivtsov, 1989). However, the problem of "specialization" of geological space still remains controversial. Recent investigations show the presence of oxidized ores with high metal contents in oceanic basalts (Procoptsev and Procoptsev, 1990) and ore liquates in feldspar and clinopyroxene in alkaline basalts (Akimtsev et al., 1993). It has been noted (Rekharski et al., 1983; Barnam, 1983) that Cu possessing comparable energy of breaking chemical bondings with protoxide iron, magnesium and calcium, can be a part of Mg-Fe silicates and, in case of sufficient amount of sulphur, can also be separated in the form of sulphides. Sharapov et al. (1999) indicate that the salinization of porous space in intrusive rocks takes place within the temperature range of 950-650°. Drop-shaped aggregates in intrusive rocks are represented by solid solutions of FeS-NiS-CuS, troilite, pyrrhotite, pentlandite, cubanite, chalcopyrite, sphalerite. Judged by these data and backing the convective model of development of hydrosystems of Cu-Zn-pyrite deposits we can assume that the concentration of ore-forming elements was facilitated by the following successive natural processes: crystallization and liquative differentiation of basic magmas followed by the interaction between the overheated surface waters and "specialized" magmatites.

In case of barite and barite-polymetallic deposits, taking into account their connections with the geological space, it can not be excluded the participation of high-mineralized (> 350 g/l) evaporitic waters in the ore genesis. These brines are distinguished by high content of Ba, Ca, Zn, Pb, Cu and Mn (Weissberg et al., 1982; Kholodov and Kiknadze, 1989; Goleva, 1993).

Hydrothermal solutions forming hydrothermal-sedimentary deposits (Butuzova, 1989), are considered to be metamorphosed marine waters. By their salinity they are close to common marine water but differ from the latter by lower content of Mg and SO^{-2}_4, high content of K, Ca, Si, and enrichment by several orders in Fe, Ag, Pb, Cu and Zn. The scope of hydrosystems convectioning around intrusions (energy source) may be defined by the so-called prophylite areal - the area of their influence on the country rocks. Data on the isotopic composition of hydrogen in fluid inclusions and oxygen in quartz, barite and calcite in epigenetic barite-polymetallic ores (Bolnisi district of Georgia) have been interpreted in favour of a considerable role of meteoric waters in ore formation process, whereas the data on Cu stock-works indicate that meteoric water in hydrosystems was of less importance than magmatogenic one (Kekelia et al., 1991).

Some authors (i.e. Hannigton et al., 1986; Elijanova, 1999) explain the zonality in unmetamorphosed hydrothermal-sedimentary ores by redistribution of ore-forming components, from lower levels to upper ones, by solutions diffusing through ore concentrations. As an example it may be adduced the Explorer Ridge in the Pacific where high-temperature sulphides of Cu and iron underlie a layer of more low-temperature iron-Zn sulphides, barite and silica. Grychuk (1999) has proposed a thermodynamic model of convective hydrosystem very close to natural system comparable with the Cyprus type in which the evolution of the hydrothermal solutions and mineral replacements within an ore-body is assumed. "Embryonic" anhydrite-pyrite concentrations in due course are replaced by a silica-sulphide matrix; sphalerite precipitates in the peripheral zones whereas, in the central parts, pyrite is replaced by magnetite and appearance of Cu sulphides takes place.

Anhydrite precipitation in the subsurface zones of "ore hills" can also be explained by supplanting near-bottom waters into discharge zones by high-temperature fluids (>300°C). Near-bottom sea waters are heated to 160°C resulting in the anhydrite precipitation (Cherkashev et al., 1999). The processes occurring in the "ore hills" may have their paleoanalgues, most likely, in the deposits of Kuroko type.

In depressions filled with oozes containing hydrogen sulphide, the mechanism of ore formation seems to be somewhat different. Judged by the regular rhythms identified within ore deposits, the precipitation of ore material was realized intermittently over vast oxidative-reductive and geochemical barriers. The example of such a situation is the Filizçay deposit, while its recent analogue may be the Red Sea whose axial zone is filled with evaporites and pyroclastolites (Degens and Ross, 1974).

In the Kuroko type epigenetic and hydrothermal-sedimentary deposits, the initial stage was characterized by entering Ba^- and Ca^- containing brines into the solfataric zones as a result of which there were formed spatially separated barite and anhydrite deposits. The latter, in due course, turned into gypsum deposits. The disconnection of calcium and barium sulphides (the latter occupy higher levels of low-temperature zones) can be explained by the different temperature regimes of their precipitation from solutions and also by the retrograde solubility of anhydrite (Holland et al., 1982); Ovchinnikov, 1988). Simultaneous precipitation of sulphides and sulphates noted in latter barite-polymetallic ore bodies, becomes possible (Franklin et al., 1984) under minimum values of PO_2 coinciding with the lower boundary of barite stability field and equal activities of H_2S-SO^{-2}_4. The zonality in distribution of sulphides of Cu, Pb and Zn in polymetallic ore bodies was conditioned, most probably, by the activity of S^{-2} in the discharge zones. It is supposed (Kraynov et al., 1988) that the efficiency of the hydrogen sulphide barrier is conditioned by small concentrations of S^{-2}. It is also possible that $\sum S$ in discharge zones was sufficient for Cu to precipitate, whereas Pb and Zn showed tendency to pass the barrier with changing the chlorite ligande by sulphide. In this case, anion-precipitant plays a role of solvent-complex generator.

As for Au-bearing quartzites, they are characteristic of polyformational deposits (Madneuli). The generation of Au-bearing quartz veinlets coincides, in our opinion, with the time of formation of explosive breccias and appearance of the above-mentioned hydrochemical zonality within the volcanostructure. Precipitation of Au, quartz and small amounts of sulphides can be regarded as an one-act process related to the destabilization of the fluid of magmatogenic nature under the conditions of high oxydative potential accessible at the level of secondary quartzite generation.

CONCLUSIONS

The above-stated material allows to make an inference that volcanism and ore formation are interrelated processes accompanying the convergence and divergence of lithospheric plates. During the divergent stage, there occurred a rise of mantle material (tholeiitic basalts and, in lesser degree, plagiogranites) to the surface along the rift zones. At some distances from the rifts where the influence of continental blocks was essential enough, volcanites have different - crustal and mantle - sources (basalt- andesite- dacite- rhyolite accumulations). Within the rift zones there were originated Cu-bearing (with small amount of Zn) ore forming systems, whereas, in the regions with well-developed continental crust, polymetallic ores concentrated in the ooze sediments of deep marine depressions.

The subduction stage is characterized by wide-spread andesitic island arc volcanism: first, within the ensimatic fore- and intra-arc volcanostructures mainly Cu-bearing systems functioning; later, they are supplemented by Cu-Zn-bearing systems (sometimes with Pb as well). The examples of the first are the Lesser Caucasian epigenetic deposits; the second - volcanogenic-sedimentary and epigenetic deposits of the East Pontic metallotect.

During the transitional (from divergent to collisional) stage, the rapid change of submarine volcanism by subaerial took place; there were formed the antidrome and intermittent series of volcanites accompanied by also intermittently functioning diversified systems. At this time, both mono and polyformational deposits appeared; the example of the latter is Madneuli.

Metal solvents in fluid systems of Cu-Zn volcanogenic deposits were mainly sea waters metamorphosed under the influence of intrusions thermal field and enriched in magmatic exhalations, whereas the metal solvents of baritic and polymetallic deposits were potash-chloride solutions of evaporitic sequences.

The following conditions are obligatory for the origin of ore formation systems: 1- the presence of "specialized" geological ore-bearing environments (basic and medium-acidic volcanites, saliferous sedimentary sequences); 2- source of sulphur (biogenic and endogenic); 3- stable energy supply (intrusions); 4- prolonged and stable functioning of physical and geochemical barriers; 5- sufficent amount of solvents. All these conditions, as has been shown, are realized at the early stages in rift troughs, and later - in marine basins within deep structures which originally might have had a transform character.

Finally, it should be noted that the collision of microcontinents accompanied by their distinction and heterogenization, as well as the shallowing of sea basins, are not favourable to a large-scale volcanogenic ore formation. At that time, one can observe the increasing role of plutonogenic (Cu-Mo-porphyry and Au-bearing), skarn rare-metal, and magmatogenic Pb-Zn, Hg and As deposits.

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