Proceedings World Geothermal Congress 2005
Antalya, Turkey, 24-29 April 2005

Hydrothermal-Magmatic Systems as the Basic Source for Energy and Mineral Resources in Areas of Recent Volcanism

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Keywords: volcanism, hydrothermal-magmatic, systems, complex, geological-geochemical, geothermal, mineral-ore forming, models, resources

ABSTRACT

The purpose of this work is creating the complex geological-geochemical model of evolution of a typical long-living (beginning from thousands and up to hundreds of thousands years and even more) hydrothermal-magmatic ore-generating system of the Kuril-Kamchatka insular arch. This model is considered as the basis for development of estimation and safety use of the richest thermal, water and mineral resources of recent and ancient volcanism areas. Specific examples were used to ground existence and show formation stages of hydrothermal-magmatic ore-generating systems of the area of ocean-continent transition. The hydrothermal-magmatic system geological structure is studied and thermo-controlling zones as well as ore-controlling ones are distinguished. The structure of areas of near-surface and abyssal solution intensive mixing and water boiling as well as geochemical barrier zones is shown. Native metals and intermetal compounds formed in the most permeable tectonic structures under conditions of "dry" reductive fluid circulation are identified. New conceptual models of hydrothermal-magmatic ore-generating systems are offered. Conditions existing in the bowels of hydrothermal-magmatic systems of insular arches result into generation of large hydrothermal deposits and formation of mineralization of auriferous-polymetallic and, probably, copper-porphyric type.

1. INTRODUCTION

Studies, exploration and exploitation of geothermal deposits have been long conducted in many countries: Italy, New Zealand, Island, Indonesia, Philippines, USA, Nicaragua, Japan etc. In recent years the issue of extraction of thermal and electric energy from fractured deep-level rocks has been dealt with in some European countries – Germany, Switzerland, France etc. In large, this trend of fundamental science and technology – the study and exploitation of geothermal deposits – has good social and economic prospects worldwide. Russian scientists gained a significant experience in study and exploitation of near-surface low temperature therms and vapor hydrotherms deposits. Nevertheless, exploration and exploitation of deposits in Russia are still at the level of pilot production. Beside general economic reasons, it is due to instability of many parameters of near-surface deposits and the complicated structure of hydrothermal systems in the deep levels.

Near-surface geothermal deposits are characterized by low P-T parameters and limited resources with a heat carrier having aggressive properties. These factors induce fundamental science and geothermal energy operations to study the deep levels of hydrothermal systems. However, the researches are carried on is specialized, that does not give possibility to create complex model of evolution of long-existing ore-forming hydrothermal system. J.Hedenquist with coauthors developed a general concept for development of geothermal and ore-forming processes (Hedenquist et al., 1996).

The development of conceptual models for formation conditions of epithermal ore and geothermal deposits, deep drilling of present-day hydrothermal systems and data on the composition of a restored endogenic fluid allowed to make the definition of volcanic-magmatic-hydrothermal systems (Giggenbach et al., 1990). Based on a large joint team research work at volcanoes and hydrothermal systems of present-day and ancient island arcs, we located long-living ore-forming hydrothermal-magmatic systems.

2. THE HYDROTHERMAL-MAGMATIC SYSTEM TYPES

The high-temperature hydrothermal-magmatic systems under study belong to the systems associated with insular-arch andesite volcanism according to the geological-hydrochemical classification by R. Henley and A. Ellis (Henley, Ellis, 1983). The near-surface geological structure and local hydraulic gradients are of great importance for the formation of high-temperature system discharge centers. At the same time it is well known that the hydrothermal cell abyssal part is concentrated around subvolcanic bodies (intrusions?) located within the boundary of the tectonic-magmatic structure axial zones (the Vernadskogo and Karpinskogo volcanic ridges in Paramushir island, the Ivana Groznogo volcanic ridge in the central part of Iturup island and the Kambalny one in the south of Kamchatka). As a rule small intrusions of andesite volcanoes are manifested in the form of circular structures tracing the ridge axial zones. The volcanic ridge geological structures determine space distribution of supply, heating, drainage and discharge areas of the thermal water. Interaction between hydrothermal solutions and including rocks causes increase of their mineralization. Hydrothermal chemical compositions as well as their temperature are the basic factor controlling solubility of mineral and gases. Besides, it also influences upon the type and mineralogy of hydrothermal reactions. Sulphur plays an important part in the composition of hydrothermae and minerals formed by hydrothermal solutions. The series of geologists studying the recent and paleohydrothermal ore-forming systems mark out two types of high-temperature ($T>150^0$) hydrothermal systems as per sulphur oxidation condition: low sulfidation and high sulfidation (Hedenquist, Houghton, 1987).

Majority of recent hydrothermal-magmatic systems belongs to the "low sulfidation" type. There H_2S is a dominant sulphur-containing compound in the convective cell upper part. The temperature in hydrothermae is 170-270^0 C at the depth 50-1000 m. The diluted chloride hydrothermae are he basic type of solutions in such well-studied systems. In the chemical composition of hydrothermae chlorine in a dominant anion and it is accompanied by Na^+, K^+, Ca^{+2} and silica as well as by gas with varying concentrations (mainly by CO_2 the quantity of which can prevail over chlorine and H_2S) and there are small concentrations of other elements including metals. The water that is meteoric in its basis and that circulates down to the depth ≥ 5-10 km is heated by magmatic bodies and rises up to the surface resulted from free convection. Two the most important physical processes influencing upon chemism of hydrothermae in the hydrothermal system bowels is boiling and dilution. In proportion as liquid high-temperature hydrothermae rises equiponderant pressure decreases and they can pass through the boiling point under the given pressure. At the depth 1000 m for pure water it occurs under the temperature T = 300^0C. If diluted CO_2 is present in the amount 4 mass% then boiling starts from the depth 2200 m. When CO_2 quantity is less the boiling point of abyssal hydrothermae is located within the boundary of interval 1000-2200 m. The process of boiling is accompanied by loss of heat taken for steam formation as well as by loss of diluted gases. This causes sudden alteration of the residual hydrothermal solution chemical compositions. CO_2 loss causes increase of pH and precipitation of some salts (minerals). Also boiling facilitates migration of steam and gas to the surface. If a steam-gas mixture meets subsurface waters (ground and leakage) steam is condensed thereby heating them and H_2S is oxidised resulting into formation of sulphate waters heated by steam under the temperatures of 100-150^0C. These acid sulphate hydrothermae produce near-surface argillization with formation of the complex of minerals such as alunite, kaolinite, native sulphur and cristobalite. In the recent hydrothermal-magmatic systems relatively cool acid waters are located along the boundaries of the uprising flow of neutral liquid hydrothermae. Carbonaceous thermae together with cool ground waters often serve as a diluent of abyssal chloride hydrothermae.

Research of the systems of high sulfidation type was started due to exploring auriferous epithermal deposits. Enargite, pyrit, tennantite-tetrahedrite, covellite and/or alunite and often porous quartz that is the product of hydrolytic leaching are found in the hydrothermally altered rocks of this deposits. The ore zones which are strictly localized by the structural elements and connected with the breccia formed by phreatic eruptions occur everywhere in the narrow interval of depths – often within first dozens of meters. Gradual transition from leached residual silica to quartz-alunite, quartz-kaolinite, clays (illite-montmorillonite and smectites) and propylitization zone is observed (Stoffregen, 1985). Kaolinite, dickite, pyrophyllite, diaspore, K-mica, native sulphur, barite and anhydrite are the important compound in the enclosing rock. The mineralogical composition allow making the certain conclusion about chemism and temperature of hydrothermae responsible for the formation of the systems of this type. In the whole sulphate and chloride-sulphate hydrothermae are dominant there. Low pH (less than 2), the facts indicating that there are solutions with high mineralization (brines) and relatively oxidized conditions, high hypsometric marks of volcanogenic structures et al. are the evidence that magmatic fluid quotas in the composition of solutions of “high sulfidation” type is great (as per isotopic data it varies from 5-7 up to 9-12 %). These systems are located in the upper part of complex andesite volcanoes such as Ebeko (Paramushir island) and Koshelevsky (South Kamchatka). As a result of interaction between hydrothermae and enclosing rocks not only different forms of silica minerals are formed but also sulphide minerals: covellite, enargite and luzonite.

3. REGIONAL POSITION AND STRUCTURE OF HYDROTHERMAL-MAGMATIC SYSTEMS

3.1. The systems of progressive stage of development

According to geological and hydrogeological researches, the hydrothermal system of Baranskiy Volcano is characterized by high temperatures of a heat conductor (300-320^0C at a depth of 1000-1100 m, in some blocks - 200^0C already at a depth of 50 m), by large gradients of temperatures (up to 50^0C/100 m), by a significant heat flow in two localities – Starozavodskoye Pole and the Kipyashchaya Rechka (up to 71,000 kcal/sec total capacity). The hydrothermal system is located above the modern subvolcanic magmatic chamber and, probably, is directly related to it. From seismologic researches a depth of occurrence of the chamber is estimated to be 2-5 km (Zlobin, 1989), what corresponds to a usual position in the section of the peripheral chamber. The most recent historical eruption of the Baranskiy Volcano took place in 1951. It was of an explosive character, of an insignificant power, accompanied by a surge of resurgent material from the central crater. The structure of the region is governed by longitudinal northeastern and transverse northwestern linear tectonic faults, by the Central Iturup circular megastructure 23-26 km in diameter and circular volcanotectonic structures 12-18 km in diameter **(Fig. 1)**. The external elements of the volcanotectonic structures, as a rule, represent the limits of old calderas. The volcanotectonic structures are oriented with their long axes towards the main directions of the Kuril-Kamchatka insular arc. The Central Iturup circular megastructure, controlling the positioning of the volcanotectonic structures and present-day volcanoes, strikes northeastwards. The hydrothermal-magmatic system of Baranskiy Volcano is situated on the southwestern slope of the Late Quaternary andesite volcano of the same name at the center of the Middle-Late Pleistocene (?) Kipyashchaya caldera. The caldera overlaps the volcanic domelike uplift of the Grozniy ridge that strikes along the general Kuril-Kamchatka direction and includes several volcanotectonic structures and present-day volcanoes: Rebunshiri, Ivan Grozniy, Drakon, Machekha, Teben’kov, and the Baranskiy. The lower part of the geologic section is composed of psephite-psammitic and agglomeratic andesitic tuffs and andesitic and andesibasaltic lavas (the Parus Formation, N_2 pr). The boreholes cross the upper 600-m part of the sequence. The rocks of the Parus Formation are overlain without apparent angular unconformity by fine- to coarse-clastic tuffites, pumice tuffs and andesite lavas of the Lebedin Formation (N_2 – Q_1, lb), with the tuffaceous sedimentary rocks predominating. The thickness of the sequence is 400 m and more. The Middle-Late Quaternary andesibasaltic to andesidacitic lavas, tuffs, and tuff breccias are likely to be formed under subaerial conditions during the uplift of the Grozniy ridge. The total thickness of the Middle-Late Quaternary sequence is no less than 100-150 m. The size, thermal energy, ages, temperature of the solutions, and some other parameters of the hydrothermal system are controlled by intrusive magmatism. The subvolcanic shallow-level magmatic bodies comprise dikes and sills of andesibasalts and basalts 0.15-17.0 m thick, the extrusions of andesidacites, and thin (1-5 m) microdiorite lenses. Groups of dikes and sills lie along the lithologic and stratigraphic boundaries, namely, along to the boundary of the Parus and Lebedin formations. The roof of a large diorite body is assumed to be at a depth of 1000-1500 m. It is evidenced from the occurrence of the rocks of a peculiar kind – intrusive tuffs or intrusive (automagmatic) breccias, which usually compose the exocontact zones of gabbrodiorite to granodiorite bodies. The thickness of this zone within the given hydrothermal-magmatic system is 500-800 m, like that of the geothermal deposits of Kamchatka, which were crossed by boreholes (Struktura…, 1993). Within the hydrothermal systems, the exocontact zones of subintrusive bodies govern the temperature distribution and ore location.

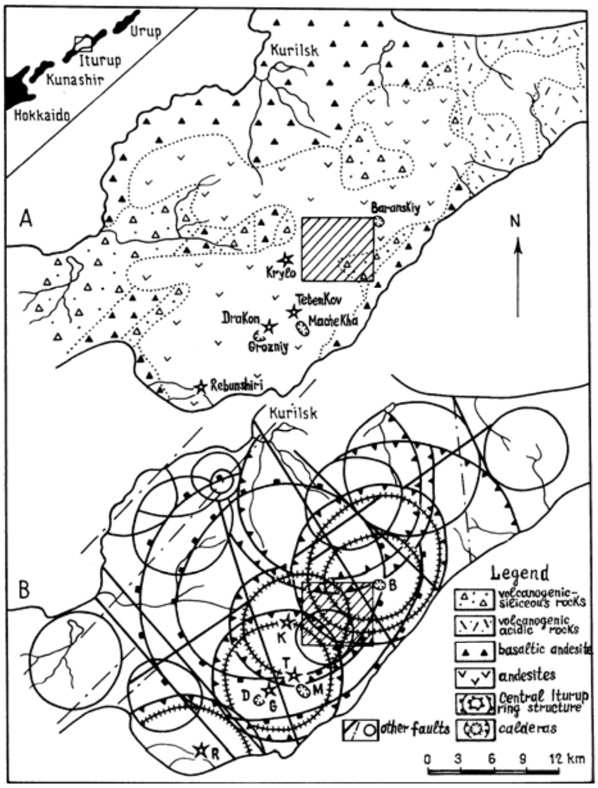

Figure 1: Schematic geological (A) and structural (B) map of central part of Iturup Island.

The rocks that accommodate the hydrothermal system of Baranskiy Volcano are altered in a variable degree by the hydrothermal-metasomatic processes (excluding the Late Quaternary unfractured andesibasalts), **Fig. 2**.

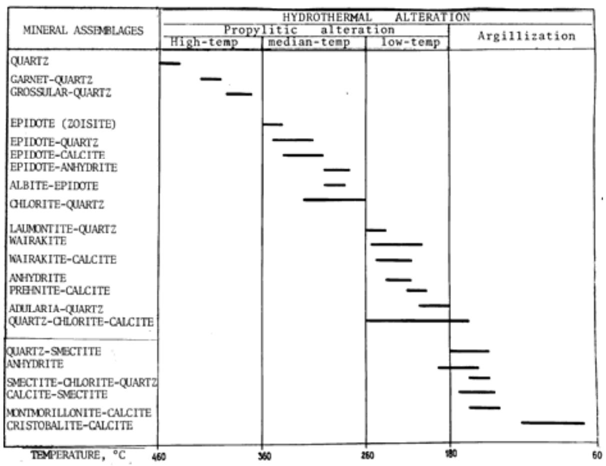

Figure 2: Hydrothermal alteration in the structure of Baranskiy hydrothermal-magmatic system (Structura…, 1993).

The bottom of the section (the Parus sequence) consists of medium to high-temperature quartz-chlorite-albite-mica propylites with epidote, zeolites, carbonates, and sulfide. According to O.P. Goncharenko's data, the temperature of the propylite formation is 350-470^{0}C (Rychagov et al., 1993). These propylites are assigned to the exocontact zone of the assumed diorite body. Low- to medium-temperature (180-300^{0}C) quartz-chlorite-calcite-zeolite propylites with hydromicas, anhydrite, epidote, and sulfides occur in the depth range from 0 (in horsts) to 500 m. Low-temperature (100-200^{0}C) quartz-calcite-zeolite-hydromica propylites with chlorite-smectite minerals generally replace the tuffites of the Lebedin Formation and Quaternary tuffs, pumices, and fractured lavas. The "cap" of opal-kaolinite-alunite rocks of the zone of sulfuric acid leaching and the products of hydrochloric-carbonic acid leaching (smectites), which overlie all other neomorphous rocks, is 50-225 m thick, in general, and up to 400-500 m thick along some faults. Due to their high viscosity, low porosity and frequent occurrence, the opal-kaolinite-alunite metasomatites and smectites serve as the upper confining bed for steam-hydrotherms. A certain type of hydrothermal alterations characterizes the "liquid-vapor" transition and vapor-dominated systems (White et al., 1971; Zhatnuev et al., 1991). The rocks are completely replaced by aggregates of quartz-adular, quartz-adular-epidote-prehnite-wairakite composition. The new formations are massive due to the quartz, adular, wairakite, prehnite and epidote filling in micro pores and cavities. Yet, they are characterized by a great amount of larger pores and cavities, formed by the leaching of initially loose and brecciated cement of wallrock, as well as by the mechanical washing of rock fragments by actively circulating steam-water mixture. The metasomatic rocks are enriched with alkaline and metallic elements: K, Li, Rb, Cs, Au, Ag, As, and occasional B. As a whole, the following distinctive features are characteristic of the hydrothermal-magmatic system of Baranskiy Volcano: polypropylites are changing successively from high- to medium-temperature ones upwardly; a block-layered distribution of the metasomatites; a high grade of rock transformation; a large thickness of the zones of acid leaching and liquid-vapor transition zones.

The present-day hydrotherms, being formed in the hydrothermal-magmatic system of Baranskiy Volcano, were discussed in a greater detail in other works (Znamenskiy, Nikitina, 1985; Taran et al., 1995). It was established that the main peculiarity of the localization of the hydrotherms is a hypsometric stratification of their types: the upper portions of volcanic structures contain solfatares; the slopes of the volcanoes and their feet hold sulfite-acidic hydrotherms of surface formation with a mixed cation composition, as well as ultra-acid sulfite-chloride therms, linked with dissolution of products of volcanic emanations and rocks of silica in the underground waters. There occur low acid and subalkaline surface springs, formed by the mixing of surface and underground waters at some distance from the recent volcanic cones. At a greater distance, the chloride-sodium springs discharge the subalkaline hydrotherms, enriched with $-CO_3$ ions and having a regional occurrence. As a whole, the noted general features of the localization of hydrotherms within the volcanic structures may as well be referred to Baranskiy Volcano. Starozavodskoye field is located at the upper hypsometric level 300-450 m within the horst structure, where steam jets and sulfite low-mineralized waters (with pH 2.5 to 5), heated by steam, are discharged. Low grades of pH are conditioned by a high content of hydrogen sulfide (up to 52%) in the water of the main geothermal reservoir, and by oxidation of hydrogen sulfide by a flow of downward underground waters, saturated with atmospheric oxygen. Yet, the drilled boreholes have introduced water-steam mixture (with a content of chlorine 200 to 3500 mg/l) on the daylight surface. This is indicative in favor of existence of a zone of underground chloride-sodium waters under the Starozavodskoye field. Subneutral diluted chloride-sodium 70^0C waters are discharged at the base drainage level (Valley of the Sernaya river). By origin, the waters are a blend of deep-level ascending waters and surface descending ones. A share of the depth component is considered to be no higher than 15%, and the cation part is formed on account of rocks, leached by sulfite therms (Taran et al., 1995). The field of **"**Kipyashchaya Rechka" is located at an absolute height of 100-400 m. Here, ultra-acid boiling waters of a sulfate-chloride composition and hot mixed chloride-sulfate waters with pH<4 are discharged. Spatially, the field is confined to the horst. Within this horst at a low hypsometric level the springs of heated carbonate waters typical of marginal parts of hydrothermal-magmatic systems or for a zone, delineating the ascending flux of hydrothermal fluid.

The data presented above suggest that an active of hydrothermal and metasomatic alteration is going on in the volcanic, volcano-sedimentary, and intrusive rocks of the Baranskiy hydrothermal-magmatic system under the effect of high-temperature (300^0C or more), fissure and fissure-pore H_2S-CO_2-SO_4 and Cl-Na-CO_2-NO_2 waters. The medium- and high-temperature propylites (300-450^0C) of the quartz-chlorite-albite-mica composition occur at the base of the sequence (more than 500 m below the surface) or in the contact aureole of the inferred large diorite body. At higher levels they are replaced by low- to medium-temperature quartz-chlorite-calcite-zeolite propylites. The process of propilitization is terminated by the formation of quartz-calcite-zeolite-hydromica rocks with abundant mixed-layer illite-smectite minerals and montmorillonite. The temperature of modern solutions coexisting with these propylites is not more than 180-200^0C. Thus, the conditions of the high- to medium-temperature propylitization changes upward to a low-temperature environment. This correlates with changes in the composition and temperature of hydrothermal fluid that is presently circulating in the system and is controled by the geologic structure of the field **(fig. 3)**.

The liquid-vapor transitions zone is formed under different thermodynamic and geochemical conditions. The hydrothermal mineral formation occurs there in a wide temperature range, from 300-250 to 200-170^0C and lower. This fact indicates an abrupt drop of rock temperature in the course of hydrothermal boiling due to adiabatic expansion. The onset of boiling may initiate the inflow of cold meteoric or sea water through open faults. Within the Kuril-Kamchatka region, active seismic and tectonic processes facilitate the opening of tectonic fractures and the penetration of meteoric and sea water. The emplacement of intrusions under enhanced seismic activity may accompanied by the interaction of magma with sea water. B. Markovskiy and V. Rotman (Markovskiy, Rotman, 1988) demonstrated that, whatever the magma composition, this results in instant water evaporation, explosion, and fragmentation of the solidified magma and surrounding rocks. Hydrothermal solutions cool off rapidly. Such zones of abrupt rock cooling are marked by the occurence of anhydrite. Anhydrite was formed under similar conditions in the altered basalts of the Reykjanes geothermal field, Iceland (Geptner et al., 1987), where the confinement of anhydrite to shatter zones a the maximum temperature drop is explained by the inflow of cold sea water into the hydrothermal-magmatic system because of tectonic adjustments. Thus, the penetration of significant masses of meteoric or sea water into a high-temperature system may initiate rock shattering and cooling, in particular, during the formation of liquid-vapor transition zones. These zones are geochemical barriers for Au, Ag, K, As, base metals, and rare alkalis (Rychagov, 1993), which record P and T drops along with changes in the composition and phase state of the fluid. Metallic elements may amount to high concentrations in lenses and veins varying from a few centimetres to tens of meters in thickness. The zones of liquid-vapor transition are commonly found in horsts.

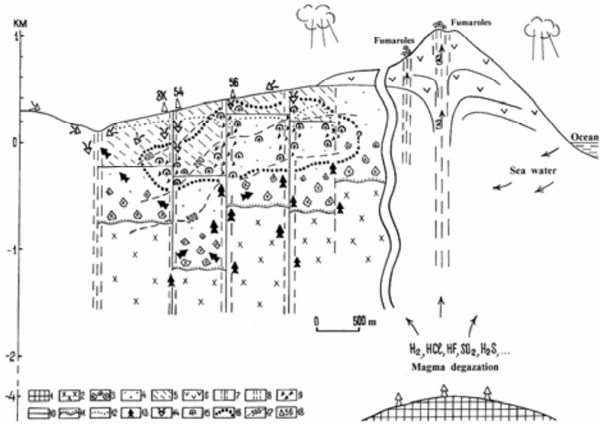

Figure 3: The geological-geochemical model for the present-day Baranskiy hydrothermal-magmatic system. 1-Magmatic chamber; 2-subintrusive diorites; 3-intrusive tuffs (breccias); 4-Parus sequence; 5-Lebedin sequence; 6-Quaternary andesites; 7-tectonic faults, proved; 8-Same, probable; 9-hydrothermal breccias; 10-Lithological boundaris; 11-intrusive boundaries; 12-boundary of distribution of argillizities; 13-ascending flux; 14-descending flux; 15-vapor-dominated zones; 16-zone of ore mineralization. 17-isotherms; 18-boreholes.

3.2. The systems of extremal stage of development

Mutnovskaya hydrothermal-magmatic system (the South Kamchatka) it´s the typical system of extremal stage of development. The Mutnovsky geothermal area is located on the eastern seashore of the Kamchatka peninsula 70 km to south from the city of Petropavlovsk-Kamchatsky. Geology and structure of the Mutnovsky geothermal area are defined by its disposition in graben-syncline of the South Kamchatka (Vakin et al., 1976). Boundaries of geothermal areas, according to V.V.Aver'ev, must be traced with isotherms joining a single front of heat feeding present-day hydrothermal systems which are localized in this area. Since in 60s and 70s Kamchatka hydrothermal systems were weakly studied in depth and in area (an insignificant amount of geothermal drilling was performed only at Pauzhetka and Paratunka fields), there has been no practical possibility to use these fundamental principles. Geothermal areas **(fig. 4)**, located along the Eastern volcanic belt of Kamchatka (Pauzhetka, Mutnovsky and Uzon-Semiachik), are connected with the regions largest negative gravitation anomalies. They are the most heated sections of the earth's crust, and they possess great amounts of acid material, thrown up in the Middle-Upper-Quarternary time. It is suggested that high-temperature hydrothermal systems such as Bolshe-Bannaya, Severo-Mutnovskaya and Zhirovskaya, located near Tolmachev gravity anomaly, are united within a single geothermal area. The downfold zone of the top of Cretaceous basement of the South Kamchatka

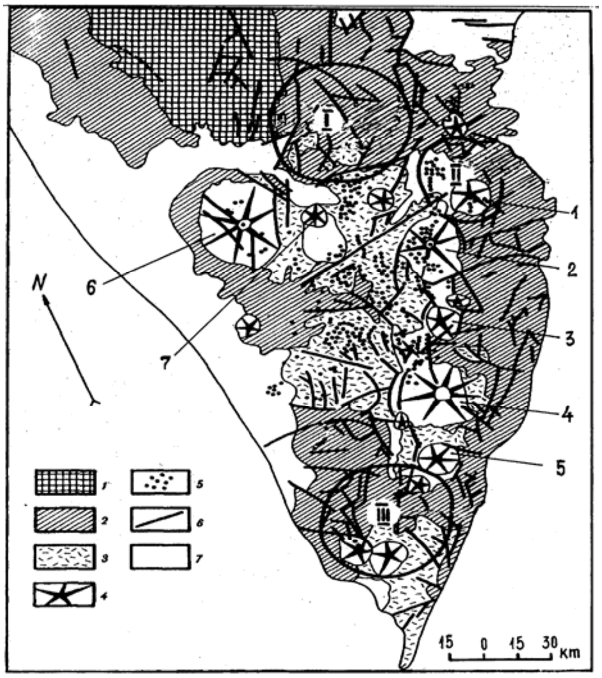

Figure 4: Geological regional setting of the Paratunsky (I), Mutnovsky (II) and Pauzhetsky (III) geothermal areas in Kamchatka (Belousov, 1978). 1 - Rocks of cretaceious and pre-cretaceous basement; 2 – rocks of paleogen-neogen age; 3 – volcanogenic and volcanogenic-sedimentary rocks of pleistocene-holocene age; 4 – stratovolcanoes; 5 – zone of areal volcanism of the South Kamchatka and secondary monogenic volcanoes; 6 – faults; 7 – coastal and lacustrine deposits. Numerals indicate volcanoes: 1 – Mutnovsky, 2 – Asachinsky, 3 – Khodutka, 4 – Ksudach, 5 – Zheltovsky, 6 – Bolshaya Ipelka, 7 – Opala.

coincides with the central part of the geothermal area where the main mass of quaternary effusives is localized. A depth of occurrence of the Cretaceous basement here is ≤ 3 km, at some sections > 3,5 km. The width of downfold is ≥ 40 km. The extension of downfold within Ksudach and the Khodutka volcanoes is faulted by the zone of north-west strike, which is traced from Khodutka volcano to the volcanoes of Opala and Bolshaya Ipelka. This zone can be accepted as a west-south-west geological boundary of the Mutnovsky geothermal area. In the East the area is framed by Cretaceous basement zone uplifted to a depth of ≤ 2 km. The northern boundary of the Mutnovsky geothermal area is Nachikinsk fold-block uplift. As is shown above, the Mutnovsky geothermal area presents a slightly submeridionally extended depression. The basement of the section in the central part of the structure is composed of Cretaceous basement rocks and of Palaeogene-Neogene volcanogenic and volcanogenic-sedimentary deposits; the upper part of the depression is filled with pyroclastics and with lavas of Pliocene-Quarternary age. In the North and in the East the structure is framed by Palaeogene-Neogene volcanites elevated to absolute altitudes ~ 1000 m. The depression of the Mutnovsky geothermal area is dissected by an intensive tectonic fracturing. Dominant faults are parallel to the strike of the main structure and are extended submeridionally, and dissecting fractures are latitudinal. Tectonic blocks are step-faulted in direction of the depression axis; along the strike the structure is bounded by tectonic-magmatic elevations. So, we assume, that the Mutnovsky geothermal area is located in the tension zone, conditioned by regional and local reasons.

Palaeogene-Neogene volcanogenic and volcanogenic-sedimentary rocks, having high fracture permeability, constitute a water-bearing complex, the structure of which is distinguished by a significant complexity in section and on the strike. Pliocene-Quarternary formations are less permeable except for lava flows, dissected by contractional fractures. The rocks of Pliocene-Quarternary age often occur upon layers of loose or weakly baked pyroclastics, compacted by ancient hydrothermal processes, or upon volcanogenic-sedimentary and sedimentary deposits. These layers and deposits act as a relative upper water-confining stratum. The structure of the upper water-confining complex is complicated, its continuity is disrupted by numerous dykes, extrusions, maars, diatremes and fractures. These geological bodies intricately influence the structure of the water-confining complex. For instance, dykes, composed of hydrothermally intact but highly fractured basalts and andesite-basalts, are good drains for descending waters of surface formation. In case when dykes occur in the zone of influence of acid hydrotherms which transmute basalts into clays, swollen when water-saturated, basalts become completely impermeable and act as a local water-confining stratum. Rocks of andesite and dacite composition under the influence of acid hydrotherms transform into siliceous rocks, which may also contain chlorite-smectites and micas. Silicification and argillization of rocks significantly reduce permeability of magmatic bodies included into the structure of the water-confining complex of the Mutnovsky geothermal area. Holocrystalline intrusions of gabbro and diorites localized beyond tectonic deformation zones are practically impermeable too. It is assumed, that the intrusive mass of Akhomten granites (the east seashore of Kamchatka), confining underground run-off towards the Pacific Ocean in the Mutnovsky geothermal area and thereby entrapping capacities of the area's hydrothermal systems, plays the role of a dam for infiltration waters. Rocks composing extrusions near intensive circulation of steam hydrotherms underwent hydrothermal metamorphosis. Extrusion rocks transform into caolinite and montmorillonite clays or opalitic siliceous formations under influence of steam-heated hydrotherms (acid solutions of surface formation) or under influence of acid deep-level hydrotherms a significant part of which consists of high-temperature magmatic gases. These processes reduce permeability of the upper parts of extrusions, and they act no more as drains feeding deep-level water-bearing complexes with meteoric waters. Accordingly, nearsurface hydrothermal activity in the Mutnovsky hydrothermal area leads to formation of broad fields of argillized-opalitized rocks acting as an additional thick water-confining layer and a heat insulator.

The analysis of the regional geological setting of the Mutnovsky geothermal area suggests that it presents an artesian super basin of an irregular-isometric shape extended submeridionally with an area of ≥ 5000 km^2. Water feed of the artesian basin takes place by means of infiltration of meteoric waters through Paleogene-Neogene rocks disclosed at the daylight surface and also, due to descending movement of waters along vertically positioned structures of volcanogenic origin unaffected by an intensive hydrothermal metamorphism. As is shown above, the Mutnovsky geothermal area is structurally and genetically connected with the crust tension zone of a regional or local character and its heat feed is provided by energy generation sources arranged within the interval of depths from the mantle to the upper crust (fig. 5). Since the earth's crust of the region underwent through the stages of formation of submarine volcanic ridge and double island arc, we assume that the interior of the Mutnovsky geothermal area contains metamorphic volcanogenic-siliceous formations (this also is supported by some geological data). During the long evolution of deep-level (basaltic) magmatism, widely manifested on the territory of the Mutnovsky geothermal area, volcanogenic-siliceous deposits containing a large amount of diffused and massive agglomerates of sulphides (pirite, pirrotine and others.) get through to the heat influence zone caused by basaltic melts. High temperatures (800-1000^{0}C) cause oxidation («combustion») of sulphides and, perhaps, of some other minerals with release of a great amount of heat energy. An intensive influx of atmospheric oxygen to hydrothermal-magmatic systems activates exothermic chemical reactions. A large amount of volcanogenic-siliceous formations and formation of sulphides, as well as native sulphur and other minerals at all stages of hydrothermal metamorphism down to newest allow to predict the presence of a large long-existing renewable heat source in addition to the traditional magmatic one. Moreover, generation of additional (secondary) heat due to high sulphides oxidation temperatures ($\geq$ 700-800^{0}C) may have caused the formation of andesite and rhyolite composition melts, explosions of a freato-magmatic type, crushing of rocks at depth, and nearsurface and open explosions.

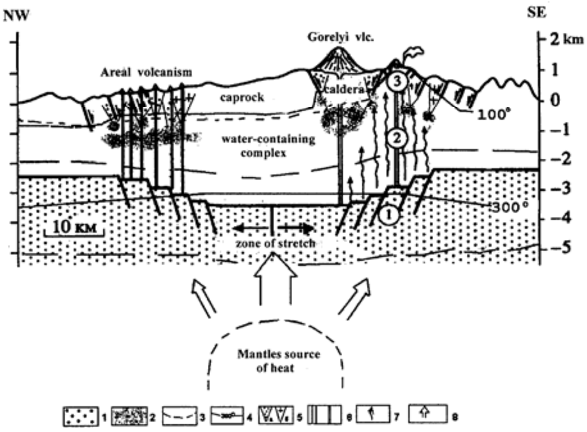

Figure 5: A conceptual model for the Mutnovsky geothermal area (used materials of V.L.Leonov, 2001). 1 – Pre-cainozoe complex of rocks; 2 – zones of crushing and collapsing in freato-magmatism manifestation areas; 3 – boundaries of development areas of volcanogenic-siliceous formations and generations of andesitic and acid anatectic melts; 4 – isotherms; 5 – diatremes and craters of explosion: a – filled with crushed rocks, b – filled with acid extrusions and effusives; 6 – dykes and magmatic channels; 7 – ascending jets of mantle fluids; 8 – direction of tensions, direction of motion of melts and deep-level fluids, generated in the upper mantle. Numerals in circles indicate: 1 – zone of fractures restricting downfold and acting as deep-level catches for magmas and hydrothermal fluids, 2 – zone of ascent of magma and hydrothermal fluids to the surface, 3 – zone of development of Late-Pleistocene fractures and faults on the surface.

Ignimbrites and baked tuffs are present within the structure of Paleogene-Neogene and Pliocene-Quarternary volcanogenic and volcanogenic-sedimentary strata what may testify of ongoing processes of formation of segregated magmatic centers within the interior of the Mutnovsky geothermal area. However, generation of segregated magmatic reservoirs similar to those of the Uzon-Semiachik geothermal area in Kamchatka or in the Taupo Volcanic Zone, New Zealand, where huge masses of ignimbrites and other pyroclastics were cast up on the daylight surface, is still at the initial stage in the South Kamchatka area under consideration. We think at present heat energy is accumulated at a depth of 5-10 km in the interior's strata of volcanogenic-siliceous formations of the Mutnovsky geothermal area, and a huge magmatic crust reservoir with a temperature of $\geq$ 700 - 800^{0}C is formed. Distribution of heat under the water-confining complexes of the Mutnovsky geothermal area takes place unevenly: relatively elevated blocks of rocks in which the top of the water-bearing complex is at higher hypsometric levels would be most heated. As a rule, structures of uplifts are conditioned by intrusions and protrusions of viscous magma and are typical for andesitic and acid volcanism.

3.3. The systems of regressive stage

Pauzhetka hydrothermal-magmatic system (the South Kamchatka) it´s the typical system of regressive stage of development. Pauzhetka long-existing ore-forming hydrothermal-magmatic convective system is localized in the central part of the Koshelevsk-Pauzhetsk volcanogenic-ore center (see fig. 4). Metamorphosed volcanomictic sandstones and aleurosandstones with thin bands of aleurolites and gravelites comprise the base of the geological section. The age of the complex is, probably, the early Miocene, a thickness is not less than 800 m. Deposits of the upper-Miocene to lower-Pliocene age of the Alney complex overlie these rocks with washout and structural discordance. The total thickness is 700-800 m. The surface of the given complex is composed of caked tuffs and ignimbrites with a thickness of not less than 150-200 m. The rocks relate to the Golygin horizon and an age is determined to be mid-Pleistocene. Deposits related to the Pauzhetka suite overlie this complex of rocks. The presence of angular disconformities and washouts allow to isolate three strata within this suite: lower- , mid- and upper-Pauzhetka sub-suites, composed of tuffs and tuffites. Flows of andesite-basalts with a thickness of 35 to 80 meters overlie the rocks of the Pauzhetka suite at the slopes of the Kambalniy ridge. Andesite-basalts and rocks of the Pauzhetka suite are overlain by dacites and andesite-dacites to rhyolites; facial transitions to lava-breccias are observed. Foots of andesite-basalt and dacites are intensively brecciated. An age of this complex of rocks is, probably, the late Pleistocene: a split of Holocene harsh stones overlies rocks. The accumulation of Miocene age sediments occurred against the backdrop of infancy of the upper mantle's intrusions and subvolcanic bodies of diorite-gabbro-diorites, accompanied by formation of dykes and sills together with effusion of lavas of medium to basic composition. Diorite intrusions are well manifested in the gravitation field in the form of intensive positive and, as a rule, subisometric in plan, anomalies. The density of driving forces, located under diorites, suggests that the lower parts of the intrusions are composed of gabbroids and more basic rocks. This conclusion is supported by observations of deeply eroded Miocene intrusions of diorite-gabbrodiorites. Within Koshelevsk-Pauzhetsky volcanogenic-ore center positive anomalies are masked by large amounts of pumice stone and acid tuffs with a low density. Diorites crop out around the center's margins and revealed by deep boreholes in the central part. Beside diorites and diorite porphyrites in the lower part of the section there are bodies of hornblende andesites. Diorites and andesites form debris in basal conglomerates of the Alney series overlying sandy aleurolitic Miocene deposits. Rocks with similar compositions occur in the form of sills and dykes in the section of the lower-Pauzhetka subsuite.

All this implies that the boreholes revealed the above apical part (exocontact zone) of a long-existing intrusive complex of diorites-gabbro-diorites in the lower part of the Pauzhetka hydrothermal-magmatic system. Magmatic activity started in Miocene and ended with introduction of the latest melts in Pliocene. The block structure of the hydrothermal-magmatic system is not homogenous. Ascending fluxes of hydrothermal fluid are confined to isometric elevated blocks of rocks **(fig. 6)**. Thermal fields at surface mark the most heated sections. The thermal fields occur at the borders of tectonic uplifts or in their axial structures. Liquid-steam transition zones and zones of loosened rocks in the form of various breccias are formed in these isometric circular blocks.

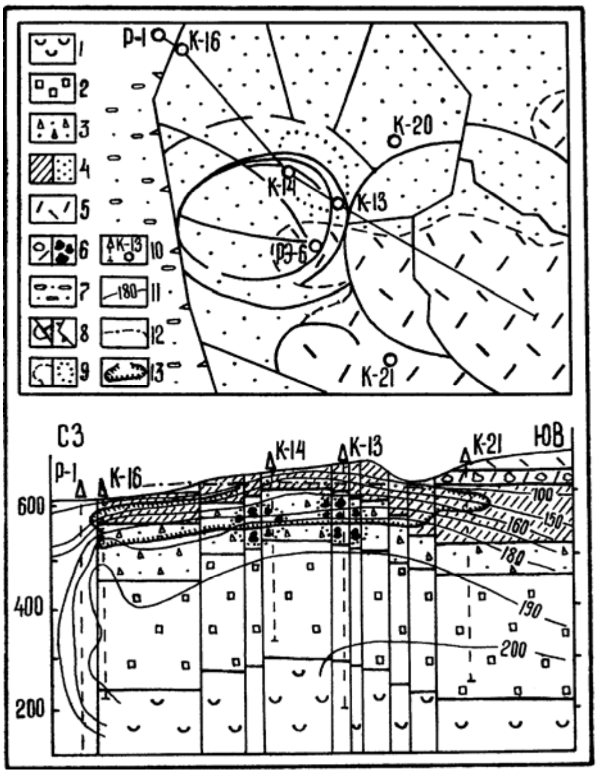

Figure 6: Geological structure of the Pauzhetka Upper thermal field. 1 – rhyolite psephitic tuffs, Golyginsky horizont; 2 – rudaceous tuffs of basalte-andesitic composition, lower Pauzhetka subsuite; 3 – psephitic tuffs of andesite-dacitic composition, middle Pauzhetka subsuite; 4 – tuffs and tuff alevrolites of andesite-dacite composition, upper Pauzhetka subsuite; 5 – middle upper-quaternary extrusions and lavas of dacites; 6 – lava breccia (a) and hydrothermal breccia (b); 7 – recent alluvial boulder-pebble deposits; 8 – tectonic disturbances (a) and Pauzhetka graben boundaries (b); 9 – thermal field; 10 – wells; 11 – isotherms; 12 – level of ground water; 13 – boundaries of vapor-dominated zone on the section.

During evolution hydrothermal processes underwent the following successive stages of alterations: a) medium-temperature propylitization (chlorite+albite+ epidote+pirite+leucoxene), within a range of temperatures of 350-330 to 280^{0}C; b) intensive and vast zeolitic (chlorite+lomontite+vairakite+analcime+ prenite) and limited Transylvanian (illite+carbonate+ quartz+chlorite+pirite+sphen) low-temperature propylitizations within a range of temperatures of 300-280 to 200^{0}C; c) hydrothermal argillization of propylites (mixed-layer minerals) within a temperature range of 200-150^{0}C. Quartz-adular, epidote-quartz-adular, vairakite-prenite-epidote-quartz-adular metasomatites at temperatures of 330-300 to 170-150^{0}C are formed in the liquid-steam transition zones during low-temperature propylitization and argillization: zones are the geochemical barrier **(fig. 7)**.

High-siliceous zeolites and dioctahedral smectite develop at a temperature of 150-80^{0}C in acid tuffs, andesites and dacites near surface. Under anomalous conditions when high-temperature isotherms were neared to surface due to intensive fracturing of rocks over the heat source, zeolitic propylites formed in the upper water-confining horizon. Clay-formation processes at temperatures below 100^{0}C occur in the thermal fields owing to chloride-carbon dioxide (dioctahedral smectite) and sulfur acid (caolinite) leaching. Successive stages of metasomatic alterations of rocks resulted in co-localization of high-temperature minerals with low-temperature ones. This supports the statement of D.S. Korzhinsky that post-magmatic hydrothermal-metasomatic processes are regressive. Thermobarogeochemical studies showed that the hydrothermal process had been multi-staged: mineral-formation occurred under conditions of temperature decreasing from 350-330 to 200-150 and to 100-50^{0}C in some separate blocks of the system. Concentrations of salts in solutions were decreasing at this. Low-temperature propylites are most common at the Pauzhetka geothermal deposit. Lomontite, i.e. intensively manifested zeolitic propylitization, marks the main ways of fluids movement. An abrupt reduction of infiltration rate and hydrotherms flow in the water-confining complexes causes the replacement of lomontite paragenesis with the calcite one and enhances formation of hydromicas in rocks. Propylites of the Transylvanian type develop in the water-confining layers. Epidote, albite, garnet and actinolite are formed in the most permeable and hydrothermally altered rocks where they associate with quartz, calcite and less often with chlorite. These minerals are relict and they characterize medium-temperature alteration of volcanites. At the present-day stage, mixed-layer chlorite-smectite and illite-smectite minerals are formed within the interior of the hydrothermal deposit.

This mineral-formation process is caused by impact of present-day fluids with temperatures below 200^{0}C on chlorites and illites formed during preceding stages of propylitization. Blocks of rocks lacking mixed-layer minerals are somehow isolated from influence of the present-day fluids.

Thus, hydrothermal-magmatic convective systems of the regressive development stage have certain peculiarities of geological structure evolution (as a rule, it is formation of thick caldera complexes and large artesian basins); they inherit the structure of hydrothermal-magmatic systems of the preceding stages (a contrast system of “hot” and “cold” blocks of rocks); gradual separation of magmatic and hydrothermal convective cells takes place in their interiors (cooling of intrusive and subvolcanic feeding bodies, degradation of an ascending flux of steam-hydrotherms, the intensive development of ore material re-distribution processes in separate blocks of the structure).

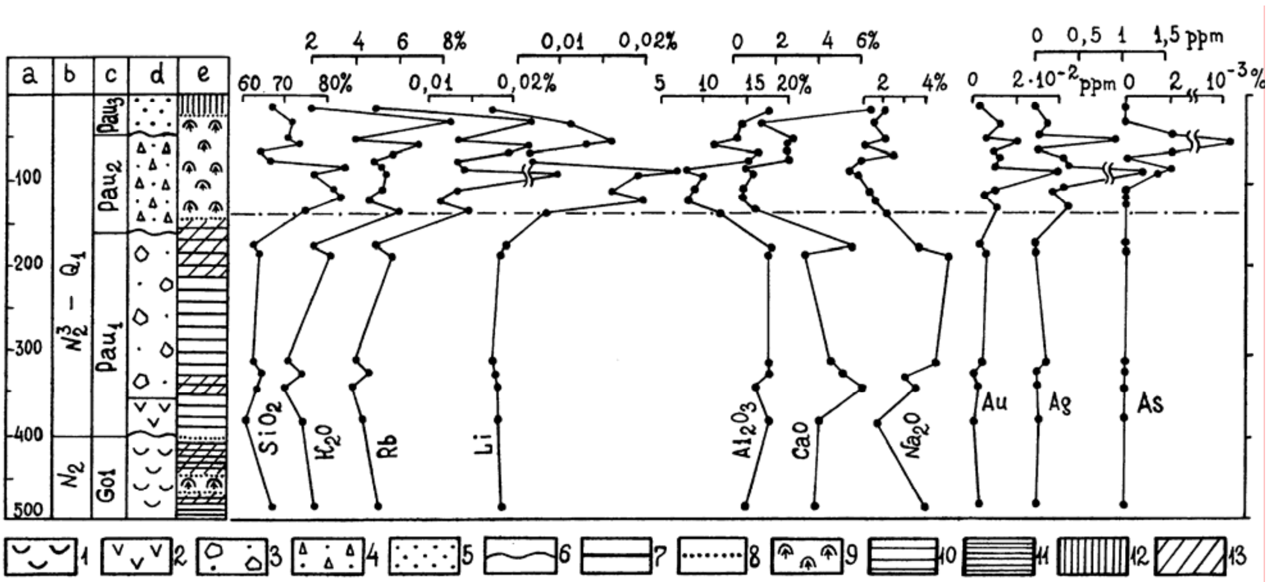

Figure 7: Cross section of well K-13 and the distribution of petrogenic and ore components in it (Structura…, 1993). In columns: a – depth, m; b – age of deposits; c – index of stratum. Go1 - Golyginsky horizon, Pau1 – lower Pauzhetka subsuite, Pau2 – middle Pauzhetka subsuite, Pau3 – upper Pauzhetka subsuite; 1-5 – symbols are as in fig. 6; 6 – geological strata boundaries; 7 – lithological boundaries; 8 – metasomatic boundaries; 9 – quartz-adular metasomatites; 10 – zeolite propylites; 11 – transylvanian type propylites; 12 – high-siliceous zeolite propylites; 13 – argillized propylities.

4. CONCLUSION: THE CONCEPTION OF GEOTHERMAL MINERAL-ORE FORMATION IN THE STRUCTURE OF HYDROTHERMAL-MAGMATIC SYSTEMS

High-potential geothermal deposits and epithermal and mesothermal ore manifestations of auriferous-polymetal type are formed as well as apparently copper-porphyritic mineralization is generated in the bowels of hydrothermal-magmatic systems of insular arches of the recent volcanism areas. Research of the transition zone between the hydrothermal and magmatic conditions proper carried out with the help of deep and abyssal wells has shown that just in this zone ore elements are deposited in the form of native metals, intermetallic compounds, solid solutions and metal alloys (Rychagov et al., 1996). This zone is the area of circulation of hydrothermae containing increased concentrations of chemical elements and first of all these are Au, Ag, As, Fe, Mg, Mn, Ti, Cr, Hg, Pb, Zn, Cu, Sn, Si, B, K, Na, Li, Rb, Cs et al. and their compounds. Hydrothermae are of great interest as the object for development of the technology of rare component extraction from them. The basic source of ore-bearing fluids is located at the depth and apparently it is associated with apical parts of subvolcanic bodies (small intrusions ?) or resent crustal and mantle hearths (Structure…, 1993). Geothermal and hydrothermal ore-generating solutions circulate inside of the complex system of permeable tectonic dislocations with break in continuity and water-bearing horizons. The thick (more than 300-500 m) steam areas the boundaries of which are the geochemical barriers for Au, Ag, As, Fe, Pb, Cu, Zn, Hg, B, K, Si and other elements are formed in the strictly definite structures (as a rule in the axial parts and on the boundaries of uplifted tectonic blocks) (Zhatnuev et al., 1991). The area of intensive mixing of near-surface acid sulphate waters with abyssal subalkaline chloride-natrium ones as well as the area of their boiling control the development of ore mineralization of “high sulfidation" type (with high degree of sulfur oxidation) in the central part of the hydrothermal-magmatic system and that of “low sulfidation” type (with low degree of sulfur oxidation) in the system periphery and at the depths more than 1-1,5 km. Silicic acid solutions and silica gel formed in the areas of liquid-steam transition and other temperature barriers are of great importance for transition and deposition of ore elements and their compounds in the structure of hydrothermal-magmatic systems. Long evolution of the liquid-steam transition areas causes formation of thick (up to 1500 m) silicification zones – adularization of rocks enclosing basic ore mineralization.

During long evolution of the hydrothermal-magmatic system from the progressive stage to the regressive one the enclosing rocks undergo profound alterations resulted from interaction with high-, middle- and low-temperature hydrothermal solutions of different composition under various pH regimes. Thick strata of propylitized rocks reaching n x 10^2 km^3 in volume within the boundary of one hydrothermal-magmatic system are formed. Argillized propylites and products of sulphur- and carbonic acid leaching the volumes of which are comparable with the above-given ones are of great importance as pre-ore or ore-accompanying metasomatites (Vasilevskiy, 1973). Many researchers have shown importance of these rocks for forming volcanogenic hydrothermal auriferous formations and generating recent ore mineralization of auriferous-argental, auriferous-polymetallic and porphyritic type. Alkaline, rare-earth and other ore elements are actively leached from enclosing rocks and at the same time many chemical components are mobilized at geochemical barriers exactly in the area of argillized propylites and argillizites.

With the help of modern high-precision analytical methods the unusual silicate and ore mineral formations – magnetic and low-magnetic spherical globules are identified deep in the rocks that are most permeable for the high-temperature hydrothermal fluid (Rychagov et al., 1996). Globules that are often hollow and high-porous consist of naive ferrum, magnetite, jocite, garnet of schorlomite type et al. and include the large spectrum of mineral phases and micro-admixtures. These minerals are formed owing to supply of the “dry” reduced fluid having temperature up to 500-600^{0}C into the near-surface horizons of hydrothermal-magmatic systems. Globules trace open down to 1,5-2,0 km heat-supplying zones of tectonic dislocations with a break in continuity in the horst structures. The hydrothermal fluid is highly gas-saturated and it is the structure-forming factor: owing to phase transitions hydrothermal brecciae are formed in the areas of boiling of steam hydrothermae, polymictic ore-bearing brecciae are formed in the near-contact parts of small intrusions or subvolcanic bodies, ore-enclosing explosive brecciae are formed in the explosion cones et al. Though in microgram quantity during all the progressive and, probably, extreme stage of the hydrothermal-magmatic system development (this duration is evaluated to be from thousands up to dozens of thousands years) the fluid introduces into enclosing rocks such elements as Fe, Mg, Mn, Ti, Cr, Cu, Pb, Au, Ag, As, Al, Si, K, Na, Ca et al. According to the data from study of sulphides the spectrum of chemical elements introduced into the hydrothermal-magmatic system is even wider (Rychagov et al., 1998). In time concentration of ore and alkaline elements-admixtures increases in hydrothermal new formations: from the high-temperature hydrothermal-magmatic system to that getting cold down to n x 10 g/t. Thus, the insular arch recent hydrothermal-magmatic systems are the analogues of primary stages of formation of mesothermal and epithermal ore deposits and, possibly, ore manifestations of copper-porphyritic type.

The work has been done with a financial support of the Russian Fund of Fundamental Research (projects 03-05-64044 a, 04-05-79051 k).

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