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Hierarchical System of Geothermal Structures—A New Outlook on Generation and Transport of Geothermal Energy in Modern Volcanic Areas

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ABSTRACT

It is demonstrated that geothermal resources of modern volcanic areas are distinctly confined to the hierarchical system of geological structures: geothermal provinces – geothermal districts – hydrothermal-magmatic systems – geothermal reservoirs (deposits). Geothermal provinces are geological structures of graben-syncline types which control regional conductive and convective heat flows. Geothermal districts are identified with long-existing volcanogenic ore centers (centers of endogenic activity) that appear on the surface as oval-circular megastructures with a diameter of 18-24 to more than 40 km. Hydrothermal-magmatic systems are crustal permeable axisymmetrical geologic structures of the type of large volcanic-tectonic structures up to more than 18-24 km in plan and forming a distinctive self-insulated convection cell (Geothermal..., 2005). Geothermal reservoirs (deposits) are not only geological-economic conception, but also represent a system of joint upstanding and downthrown tectonic blocks with a thickness of up to n x 100 m, which control local flows of ascending fluids and descending meteoric (mixed) waters. Geothermal deposits, as a rule, are located in the central parts of hydrothermal-magmatic systems, which is determined by the position of a heat (fluid) source. The paper addresses the geological setting of geothermal provinces–districts–systems–deposits, heat (ore – fluid) feed sources, hydrothermal metamorphism of rocks, dynamics of gas-liquid and water flows, a role of gases in geology of hydrothermal-magmatic systems and in heat transport, possible heat energy storage and transfer mechanisms, etc. A model for hierarchy system of geothermal structures is suggested (from regional to local) to be built upon when applying a geological approach to assessment of prospective energy and mineral resources of modern volcanic areas.
of manifestation of geothermal energy. For instance, there are hydrothermal-magmatic systems linked to the Karimsky volcanic center into a distinct geothermal district. On the other hand, both geothermal districts are located in the single regional structure of the Eastern Kamchatka rift (graben-syncline?) (in this respect we deem it logical to identify the Eastern-Kamchatka geothermal province. Comparative analysis of geological structures and hydrothermal activity within the South-Kamchatka graben-syncline allows to identify the South-Kamchatka geothermal province, which includes Paratunsky, Mutnovsky and Pauzhetsky (Pauzhetsky-Kambalny-Koshelevsky) geothermal districts (Figure 2). It is also possible to distinguish Hodutkinsky and some other regional geothermal structures. In Kamchatka, geothermal provinces were identified earlier (Smirnov et al., 1991; Sugrobov et al.,}

![Figure 1. The Scheme of Modern Structure and Volcanism of Kamchatka (have compounded by E. Erlikh in 1965). 1 – Stable zone of flatness of western coast. 2-Malkinskii crest of Oligocene-Miocene age. 3–Tigil-Palanskoe upheaval of Pliocene age. 4-Horst-Anticlinories imposed on Cretaceous and Miocene-Paleogen depositions. 5–Roof upheaval zone of accumulative-tectonic structures. 6–U upheaval of Pliocene-Lower Quaternary age. 7–Graben-Syncline of Pliocene-Lower Quaternary age. 8–Large extinct volcanos. 9–Modern volcanos. 10–Zone of areal volcanism. 11–Faults. 12–Volcano-tectonic depressions.](image1)

![Figure 2. Geothermal Areas of South Kamchatka: the Structural Scheme (Geology-Geophysical Atlas of Kuril-Kamchatka Island System, 1987, in editional by S. Rychagov). On the insertion are rotined the main structural zones of Kamchatka for Paleogen-Neogen age (have compounded by G. Vlasov and V. Yarmoluk in 1964). 1–West-Kamchatka zone. 2–Central-Kamchatka zone. 3–East-Kamchatka zone. 4–Median array. 5–Boundary of the East-Kamchatka volcanic zone. 6–Geothermal regions. 7–Geothermal systems](image2)
The South Kamchatka geothermal province is situated within the South-Kamchatka graben-syncline which was identified on the grounds of geophysical data (Figure 3). As was noted above, it is founded by three geothermal districts (See Figure 2). Each geothermal district is structurally confined to the long-existing volcanic (volcanogenic-ore) center and has its individual development history (Belousov, 1978; Dolgozhivushiy..., 1980). The Mutnovsky geothermal district is now of economic significance to Kamchatka in view of putting into operation Upper-Mutnovsky (12 MW) and Mutnovsky (50 MW) geothermal power plants and feasibility to increase an extraction of geothermal heat carrier to cover a deficit of heat and electric energy in Kamchatka Oblast (Kononov, Povarov, 2005). Previously, we proposed geological and structural underpinning to continue exploration works and extend exploitation works in view of the region’s energy capacity assessment which according to out data yielded no less than 3,000 MW for 1.5 – 2.0 km deep resources. A “surplus” capacity may be utilized for the development of technologies and for direct mineral resource extraction from thermal waters, volcanic gases, siliceous and other mineral sediments and hydrothermally-altered rocks abundant in the Mutnovsky geothermal district.

The structure of the Central Iturup geothermal district is controlled by longitudinal north-east and traverse north-west linear tectonic faults, a homonymous circular megastructure having 23-26 km in diameter and volcanic-tectonic structures with smaller diameters (Figure 4). The Baranskogo hydrothermal-magmatic system is confined to one of such volcanic-tectonic structures (VTS) with a homonymous volcano in the center. The well-known Okeanskoye geothermal deposit is located at the intersection of this VTS with the “Wing” VTS. Several ore occurrences are confined to these and other VTSs (Geologo-geofizicheskii..., 1987). Thus, the Central-Iturup circular megastructure may be identified with long-existing volcanogenic-ore center and modern geothermal district.

The Baranskogo hydrothermal-magmatic system is characterized by block structure (Figure 5). Rocks of a relatively...
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low-standing block and tectonic-magmatic highs are generally less disturbed and altered by hydrothermal solutions than horst rocks (Rychagov, 1993). Horsts are characterized by a significant geothermal heat flux to the surface – up to 71 000 kCal/sec of total capacity. Thermal discharge structures are zones of tectonic dislocations dividing the horst rocks into small blocks – plates, and boundaries of large blocks. By analogy with hydrothermal-magmatic systems of Kamchatka, main thermal discharge structures are fault zones composed of breccias: tectonic, endo- and exocontact, hydrothermal, combined polymictic. The latter are characterized by different composition of fragments, multistage formation of hydrothermal cement, multiple brecciation manifestation and contain iron, lead, zinc sulfides and native metals. The Okeanskoye geothermal deposit is practically a system which contains three conjugated tectonic blocks – horsts entitled “Starozavodskoye Pole (Old-plant field)” and “Kipiaschaya Rechka (the Boiling River)” (main discharge structures) and a relatively low-standing block, which feeds the deposits with meteoric and thermal return waters (See Figure 5). In the horsts’ interior, volcanogenic, volcanogenic-sedimentary and subvolcanic rocks are intensively transformed under the influence of high temperature (more than 300-350°C) fracture pore hydrosulfuric-carbonate-sulfate and chloride-sodium carbonate-nitric waters. Monodiorites and quartz-epidosites are originated in the endocontact zone of a large andesite-basalt subvolcanic body. Mid-temperature propylites are formed in the base of the section. Then higher the propylites are changed for low-temperature and argillized ones. The argillization drives the formation of upper water-confining and heat-insulating 50-225 meter thick horizon spread over the whole deposit area. Hydrothermae boiling sections originate under an extraordinary thermodynamic and geochemical regime. Mineral formation temperatures oscillate from 300-250 to 200-170°C and lower. This testifies that rocks’ temperature declines sharply in the process of solution boiling, possibly, due to influx of cold meteoric and marine waters through open fractures. When intrusions are formed in the high seismicity environment melt may interact with seawater. Regardless of magma composition, such interaction results in instant water evaporation thus causing an explosion which fractions the freezing melt and shatters host rocks (Markovskiy, Rotman, 1988). Hydrothermal solutions suffer “instant” cooling. Such zones of the abrupt cooling are registered, in particular, by anhydrite: anhydrite occurs in the key section of the Okeanskoye deposit at a depth of 785-925 m with a temperature drop from 460-360 to 190°C during the secondary mineral formation (Rychagov et al., 1993). Anhydrite from altered basalts on Reykjanes geothermal field (Island) is formed in similar conditions (Geptner et al., 1987). In such a way, mass penetration of meteoric and/or sea waters in the interior of a geothermal deposit functions as a launch mechanism for rock breaking and as a cooling factor, and also can cause formation of hydrothermae boiling sections and precipitation of ore, alkaline and rare chemical elements on their boundaries.

Heat Generation and a Role of Gases in the Structure of Hydrothermal-Magmatic Systems

The thermal unbalance of magmatism and hydrothermal activity in the modern volcanism areas (Hochstein, 1995) makes researchers to search for a new explanation of heat sources emergence and their functions in hydrothermal-magmatic systems. At present, magmatic melts are considered as main agents which transport heat, gases and metals and form hydrothermal solutions. The solutions impact the environment by interacting with rocks, hydrosphere and atmosphere and form geothermal deposits, occurrences of mineral and non-mineral natural resources. Participation of hydrothermal metamorphism products in hydrothermal-magmatic activity is more frequently addressed mechanistically. We presume that

Figure 5. Scheme of the Present-Day Tectonic Structure of the Branskii Hydrothermal-Magmatic System and Okeanskoe Geothermal Deposit (Rychagov, 1993). 1–3 – Middle Miocene-Pliocene volcanogenic complex of rocks: 1–silicic-diatomic, 2–silicic, 3–andesibasaltic. 4–Quaternary andesitic deposits. 5–The Parus Formation. 6–The Lebedin Formation. 7–Diorites. 8–Intrusive tuffs. 9–Contacts: a–lithologic, b–intrusive. 10–Volcano-tectonic structures. 11–Faults and boundaries of tectonic blocks. 12–Volcanoes) from SW to NE: Ivan Groznyi, Tebenkov, Baranskii. 13–The Goluboe ozero hot spot. 14–Boreholes. 15–Figure area on the inset map. The axial parts of horsts and mercury geochemical profiles are hatched in different patterns.
the generation of magmatic melts and the related hydrothermal metamorphism of rocks are caused by interactions of various chemical elements and their compounds, which bring about resultant products resistant to certain thermodynamic conditions. We recognize the hydrothermal-magmatic convective systems of the modern volcanism areas as complex chemical reactors which function in a self-sustained regime. Crustal heat sources of magmatic and, possibly chemical origin, appear at the level of the middle and the upper crust during the evolution of island arc hydrothermal-magmatic convective systems. Heat energy of crustal sources causes circulation of solutions, gradually increases the volume of a hydrothermal convective cell in a hydrothermal-magmatic system at the progressive development stage. Paragenesis of silica minerals and sulfides underlies hydrothermal alteration of rocks. Progressive accumulation of sulfide-siliceous hydrothermalites during the evolution of hydrothermal-magmatic systems may be regarded as energy storage process in the form of chemically active (combustible) compounds. The “combustion” and progressing “burning” of hydrothermalites take place under the effect of deep-seated magmatic injections resulting in emergence of an intermediate heat source - the crustal magma reservoir with relatively low temperatures of melts (800°-1000°C).

Gases with a high degree of sulfur oxidation and explosive gases are generated in island arc hydrothermal-magmatic systems. The former foster disintegration of ore-bearing anatectic melts which were formed with sulfide-siliceous hydrothermalites which had concentrated noble, polynatric, rare and radioactive elements; transport and further precipitation of chemical elements in pyroclastic rocks during neutralization of acid solutions occurs. Gases as a result of combustion and explosion split melts and break surrounding solid rocks, outburst them, create vacuum at the moment of explosion; roof rocks collapse in newly-formed open spaces, deep-rooted and crustal anatectic melts being actively degassed are injected from below, and meteoric waters arrive from the surrounding hydrosphere. Complex of these processes supplemented by oxidation (“combustion”) of sulfides and influx of atmospheric oxygen through faults towards the collapse zone leads to ignimbrite formation. This period of hydrothermal-magmatic system activity may host porphyry-type mineralization in over-intrusive zones as well as mesothermal ore manifestations in the zone of ascending fluid flow and epithermal ore manifestations in the area of lateral spreading of metal-bearing hydrothermal solutions.

It is known that volcanoes erupt large amounts of mineral, alkaline and other elements such as Mg, Mn, Na, K, Ca, Al, Fe, As, Zn, Sr, Ba, Cu, Pb, Sn, Sb, Ge, Ag, Cr, Ni, Mo etc., on the surface (Giggenbach et al., 1990). Main gas constituents in the 1970 emission of the Kilauea volcano were Na, Ca, Al, Fe, Mg, K, Ti, Zn, Cu and Ni (Naughton et al., 1974). Significant contents of elements such as B and Si were identified. Presence of heavy metals in volcanic gases is linked to their selective exsolution from magma and eventual condensation due to cooling. Later it was established that contents of metals and Si in volcanic gases are much higher than those which can be attributed to their volatility. Analyzing the status of transport mechanisms and metal precipitation within gas-hydrothermal environment, it should be noted that the issue is at the inception stage of data accumulation and conceptual model generation. The data we derived from several modern high temperature hydrothermal-magmatic systems of Kamchatka and the Kuril islands are practically the outputs of natural experimental research.

Conclusion

Identification and detailed complex study of hierarchy system of geothermal structures (provinces – districts – systems – deposits) provide for formulation of conceptual, numerical, thermohydrodynamic and eventually exploration and exploitation models of geothermal sites. Accuracy of assessments of geothermal energy resources directly depends on correct determination of boundaries and setting of geological structures, volumes and properties of water-confining and water-bearing complexes, structure and intensity of convective flows of fluids (gases, vapor-hydrothermal, mixed and meteoric waters). In particular, the study of geological structure and properties of systems “confining layer – permeable horizon” creates a solid basis for feasible heat extraction technology development. On the whole, such an approach ensures the economical feasibility of exploration works, extraction and utilization of geothermal resources of the modern volcanic areas, and that is why it may underlie the preparation of large investment projects designed to provide electrical and heat supply to population and industries of regions. As a rule, geothermal provinces are extremely rich in various mineral resources. This asset must be taken into account when making socio-economic planning for these regions and when estimating capacities of heat and electric geothermal stations.

Based on the stated above, we conclude that the Kuril-Kamchatka region is currently one of the most promising in the Russia’s Far East in terms of attraction of large domestic and foreign investments.

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