Geological Structure of the Hydrothermal Systems of Kamchatka *

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The greater part of thermal fields of commercial interest is located in the East-Kamchatka volcanic zone. The geological structure of the zone is extremely complex. It is characterized by a great facies variability of the areas. This makes the correlation of distant sequences extremely difficult.

As result of recent regional researches a number of structural-facies zones has been established for the Kamchatka geosynclinal area in the most widely developed Paleogene-Neogene formations (1964). According to these data the East-Kamchatka volcanic zone is a superimposed structure. In the north-east these rocks rest on N-Q_1 deposits, in the south of Kamchatka on deposits of Paleogene-Neogene age (see Fig. 1).

Typical Features in the Geological Structure of the Areas of Hydrothermal Activity

1. A common feature in the geological structure of the areas of hydrothermal activity is a recent volcanic activity. The forms of volcanism vary.

The extrusive type of volcanism is most intimately associated with hydrothermal activity. Sometimes extrusions form sill-like surfaces. During eruptions from near-by centres extrusive massifs can be formed, which occupy large areas. Depending upon the silica contents in the material and upon the rate of injection, the extrusions can vary in their morphology. Extrusive domes consisting of acid or sub-

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acid rocks are, usually, crowned by « obelisks », « needles » and « teeth ». When the material corresponds to the composition of andesites, andesite-basalt, the extrusions can generate minor lava flows. Usually, the extrusions are injected into tuffaceous sedimentary or terrigenous sedimentary rocks of different ages.

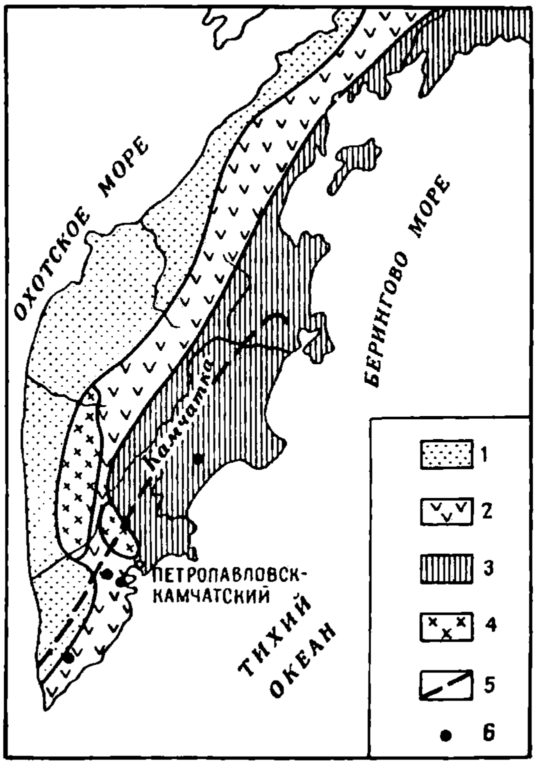

FIG. 1 - Main structural-facies zones of Kamchatka during the Paleogene-Neogene time. According to G. M. VLASSOV and V. A. YARMOLIUK.

1. West-Kamchatka zone.
2. Central Kamchatka zone.
3. East-Kamchatka zone.
4. Median massif and Ganalsk nose of metamorphic rocks.
5. Boundary of the East-Kamchatka volcanic zone.
6. Hydrothermal systems.

2. Recent hydrothermal activity within the East-Kamchatka volcanic zone develops under different structural-facies conditions. The main water-bearing rocks within the Central Kamchatka zone are rocks of the Viliuchinsk, Paratunsk and Berezovsk suites of Paleogene-

Neogene age. They are represented by terrigenous sedimentary forms from argillites to conglomerates and breccias with horizons of tuffaceous rocks.

Within the East-Kamchatka zone and along the junction between the Central Kamchatka and West-Kamchatka structural-facies zones, the water-bearing rocks consist of volcanic-sedimentary masses of Pliocene-Pleistocene age. Tuffaceous material forms the bulk of these masses.

3. As a rule, baked tuffs are spatially associated with the extrusions and the volcanic-sedimentary formations.

In some cases horizons of baked tuffs form plateau-like surfaces, being located on the divide portions of the area. They are characterized by a columnar jointing and a vertical variability in the degree of baking. Quite often in the central part of the horizons the degree of baking in the tuffs is much higher than at the roof or bottom. The baking is so intense that quite often baked tuffs are formed with lenses of glass (« ignimbrites »). This type of baked tuffs spatially gravitates towards big polygenetic volcanic structures. However, such a regularity is not always valid. Quite often big horizons of a semi-sheet type have no distinct association with definite morphologically expressed structures.

We distinguish also another type of baked tuffs. They possess approximately the same lithological features, but their peculiar structural position in the sequences of sedimentary and volcanic-sedimentary rock masses as intraformational horizons warrants an assumption of a different nature of formation. Horizons of baked tuffs of this type are found rather often. As a rule, baked tuffs exposed by boreholes in the sequences of aquifer complexes in hydrothermal systems belong to this type. Their chemical composition is close to the composition of the enclosing rock masses of a tuffaceous-sedimentary origin.

The third type of baked tuffs often found in some areas of hydrothermal activity is spatially and genetically associated with young extrusions. In this case « flows » of baked tuffs are located near the extrusions and their boundaries are distinctly discernible in the relief. This permits one to establish a direct connection between this type of baked tuffs and the immeditely adjacent extrusive bodies.

The age of the horizons of the first and third types of baked tuffs can be rather clearly dated as Upper Pleistocene-Holocene. The dates of the second-type tuffs can be conditionally determined by the age of the enclosing sedimentary or volcanic-sedimentary rock mass. However, until the establishment of the genesis of the baked tuffs of the second type, the question of their dating must remain open.

4. In some areas a wide development of pumice masses with a thickness of 100-200 m is recorded. The pumice deposits are of two types.

Pumice deposits of the first type occupy big territories in the area forming thick horizons of poorly consolidated clastic pumices. Among other places they are widely developed in the area of Southern Kamchatka near the Pauzhetka thermal springs. In the opinion of some researchers the formation of such pumice horizons is associated with catastrophic eruptions, which resulted in the creation of caldera-like structures. It is thought that the centre of eruption was located in the place of the present Kurile Lake depression.

The second type of pumice deposits is found in the Uzon depression. They form the apical parts of small extrusion. In studying such extrusions, starting from the bottom, one can observe a gradual transition from monolithic glassy andesite-dacites that make up the socle of the extrusion, through slightly porous varieties of these rocks to pumices.

One of the characteristic features of andesite-dacites is a high content of water, the amount of which comes to 4 weight percent of the total rock mass. This is most significant. Usually, glassy rocks with such a water content are heaving when heated and form light pumiceous rocks. This, apparently, is the explanation of the formation mechanism of the second-type pumices.

Typical Features in the Geological Structure of Present Hydrothermal Systems

The character of jointing and the extent of lithification of the water-bearing rocks are the main factors, which determine their filtration properties. Factors of no lesser importance are their position in space and the tectonic nature of the aquifers and of the confining horizons. According to these features the known hydrothermal systems of Kamchatka are divided by us into two types a) Pauzhetka and b) Banno-Paratunsk.

Pauzhetka type.

Among the hydrothermal systems known in Kamchatka the Pauzhetka type includes: Pauzhetka, Geysernaia and Uzon hyrothermal systems. Many features of their geological structure are identical. The water-bearing masses, the confining beds, tectonics, secondary mineral formation, and in this connection the supply conditions and ways of discharge are monotypic for all these hydrothermal systems.

WATER-BEARING ROCKS AND THE CONFINING BEDS. In hydrothermal systems of Pauzhetka type the water-bearing rocks are represented by thick masses of psephytic tuffs, consisting mostly of big pumice fragments, more rarely of andesitic and basaltic debris, the interfragmental spaces being filled by small chips of crystals and volcanic glass. The cementation is very poor. For instance, when wells were drilled at Pauzhetka an intense washing with drilling mud destroyed the rocks completely or damaged them quite badly. One of the characteristics of the extent of porosity can be the volumetric weight of the rock, which for Pauzhetka psephytic tuffs comes to an average of 1.9-2.1 g/cm^3. The average specific density of the minerals forming the psephytic tuffs corresponds to the density of plagioclases (2.6 g/cm^3). The active porosity of these rocks is still very low and jointing plays a substantial role in the increase of its permeability. The water-bearing rock masses of Pauzhetka, Geysernaia and Uzon hydrothermal systems are characterized by a poor jointing: from 0 to 2 joints per one linear meter of the sequence. Usually, these are shear joints with even, often ground edges. Only certain portions of big zones of fracture are an exception. The net of big disjunctive dislocations is also not very dense. Thus, for instance, in the discharge centre of the Pauzhetka hydrothermal system there are three zones of disturbances over a stretch of 1.5 km. Each of them consists of several « simple » faults, located in direct proximity to each other. A similar picture is observed in the structure of Geysernaia hydrothermal system.

The filtration rates of hydrothermal waters increase in the fracture zones several times, which is proved by a markedly geater yield of the wells sunk in the zone of disturbances. The permeability ratios of Pauzhetka psephytic tuffs computed by V. M. SUGROBOV (1965) by the pumping data from wells located beyond the shatter zones, are by one order below the permeability coefficients of highly jointed psephytic tuffs, which still do not exceed several hundreths darcy.

The water-bearing rocks of the hydrothermal systems of Pauzhetka type are, usually, covered by horizons that play the role of confining beds. The rocks of these horizons possess poor filtration properties and are, virtually, impermeable even for high-temperature waters.

In the sequences of Pauzhetka, the Geyser Valley and Uzon the role of confining beds belongs to horizons of aleuropelitic and pelitic tuffs. Their thickness varies from 0 to 100 m. As a rule, they are compact, highly lithified, have a conchoidal fracture, are slightly fissured. In comparing the degree of hydrothermal metamorphism in the horizons of psephytic tuffs with the thermometamorphism in the horizons of aleuropelitic and pelitic tuffs it is possible to speak about their sharply differing filtration properties. Aleuropelitic tuffs are very slightly affected by the processes of hydrothermal metamorphism, which can be explained only by a poor water exchange between the active solutions of the aquifer and the pore solutions of the aleuropelitic and pelitic tuffs.

In the shatter zones both the water-bearing rock masses and the confining beds are badly jointed. Fissured zones in localities where the water head is above the surface level, can be rich in water, which has been confirmed in drilling the wells at Pauzhetka and is established by the abundance of natural issues of thermal waters, which cross fissure zones in the Geyser Valley.

The majority of the now known high-temperature hydrothermal systems of the world, Wairakei, Waiotapu (New Zealand), Onikobe (Japan) and many others, are characterized by the same structure as the hydrothermal systems of Pauzhetka type in Kamchatka. According to the information in literature their geological structure is identical in many respects — the water-bearing rock masses are slightly porous, with a poor jointing, with a low permeability coefficient, they are overlain by impermeable horizons of compact rocks. All hydrothermal systems of Pauzhetka type are characterized by seam-pore conditions of circulation of thermal waters.

Tectonics. The supply and discharge conditions of hydrothermal systems are to a great extent determined by the specific features of the tectonics in the localities of their development. One of the decisive points in the structure of the locality is thought to be the position in space and the character of the tectonics of the aquifers and confining beds. In a regional pattern the areas of hydrothermal systems of Pauzhetka type are characterized by an undisturbed occurrence of volcanic-sedimentary rock masses. Thus, for instance, for a distance of several kilometers from the Geyser Valley up to the Uzon depression the roof of the confining horizon is at the same level.

Usually the tectonics in the areas, where these systems are developed, are characterized by local disturbances. As mentioned previously, the geological development of the areas of present hydrothermal activity in Kamchatka are characterized by a mass injection of extrusions of a varying composition. For the Pauzhetka type the chemical composition of the majority of extrusions corresponds to the average bulk chemical composition of the tuffaceous rock mass, which they are cutting.

In the process of injection the extrusions cut the mass of tuffaceous or sedimentary rocks and cause local disturbances along the periphery of the broken-up portion of the mass. These disturbances consist of an upward tilting of the beds of tuffaceous-sedimentary and sedimentary masses. Depending upon the extent of lithification of the broken-through rocks there can be either a tilting up of horizons with a break in the continuity of beds and their vertical displacement or a bending of the beds. Thus, for instance, in the area of Geysernaia hydrothermal system at a distance of 500 m the angle of dip changes from 55° at the extrusion to 20° at a distance from it.

In the majority of the extrusions the roots descend with a minor dip in respect to the horizon. As a result the assumption will be justified that it is involved in a uplift by the injection of extrusions of large portions of the territory.

In tracing index horizons in the tuffaceous-sedimentary rock mass of Pauzhetka it becomes possible to establish that the maximum amplitude of uplift comes to 1000 m. In the Geyser Valley the displacement amplitude of separate blocks by extrusions comes to 300-400 m. As result of such displacements a monoclinal occurrence of water-bearing rock masses and confining beds often originates.

If the apical parts of the extrusive bodies form a semi-circle or semi-ellipse with a block of tuffaceous-sedimentary or sedimentary rock mass in the middle, another modification of the « monocline » is possible — with a centroclinal closure. A structure of the « centrocline » type is characteristic for the geological structure of Geysernaia hydrothermal system. The Uzon and Pauzhetka hydrothermal systems are characterized by a « monocline » with sloping angles of dip.

As result of big shoves, when the rates of movement in the different parts of one extrusion varies considerably, the formation is possible of a structure consisting of big blocks within a big « monocline » or « centrocline ». The greatest amplitudes are observed nearer to the uplifted portions of the extrusions. The amplitudes of faults at a distance from the extrusions are much smaller, and, in some cases, amount to several meters, being, actually, fracture zones.

The supply area of the Pauzhetka-type hydrothermal systems is determined by the area of the inclined « monocline » (or « centrocline ») and a part of the territory occupied by the extrusions. The dip of the « monocline » determines the gradients of the water stream and affects the piezometric height. In the valleys of the rivers Pauzhetka and Geysernaia and in the Uzon depression, where the piezometric height is above the surface of the Earth, thermal waters have issues along faults perpendicular or subperpendicular to the main direction of the water stream.

The Banno-Paratunsk type.

The Banno-Paratunsk type includes a number of hydrothermal systems located in the southern part of the East-Kamchatka volcanic zone. The water-bearing rock masses are represented by Paleogene-Neogene sedimentary, pyroclastic and extrusive deposits. It should be pointed out that a considerable part of hydrothermal systems of this type, representing a commercial interest, has a temperature at depth below 100°C. Only two of the known systems — Bolshaia Bannaia and Zhirovskaia — are high-temperature systems.

WATER-BEARING ROCKS AND CONFINING BEDS. Owing to the difference in the character of water-bearing rocks the hydrothermal systems of this area must be considered as a special type. The main distinctive features of the water-bearing rock masses of the hydrothermal systems of Banno-Paratunsk type are: a high degree of rock lithification with very poor filtration properties (permeability coefficient 0.01-0.001 millidarcy) and a high extent of jointing throughout the entire rock mass independent of its lithological composition.

As demonstrated by the experience of pumping the wells, the effective permeability coefficient of these rocks is rather high. The presence of a great number of fracture zones is provided by a dense network of fissures of varying origin. For instance, one well on Paratunsk thermal field opens up one, two, and sometimes even three fracture zones. The thickness of each of these zones comes to several meters. The number of fissures per 1 meter of the well in the fracture zones is estimated to amount to several hundreds. Gaping fissures with a width of 1 ÷ 3 cm are very frequent.

The lithological composition of the aquifers is extremely varied: from argillites to conglomerates and breccia, but by the degree of lithification, and, consequently, by their filtration properties, the rocks greatly differ from each other. The sequences of the water-bearing rock masses include sills of diorite-porphyrites.

The water-bearing rock masses in the hydrothermal systems of the valleys of the rivers Paratunka and Zhirovaia are covered by loose or slightly compacted, more rarely cemented sedimentary deposits. They mostly consist of clays, sands, pebbles, and conglomerates in a series of bands. The conglomerates are found near the natural issues of thermal waters on Middle Paratunsk and Upper Paratunsk hydrothermal systems.

The structure of the sequences of Bolsaia Bannaia hydrothermal system differs only by the presence of a top confining horizon represented by aleurolite (siltstone) and compact sandstone.

Owing to the specific features of the collectors' properties of the aquifers, the Banno-Partunsk type is characterized by fissure-vein circulation conditions.

TECTONICS. In its general features the tectonics of the territories where hydrothermal systems of the Banno-Paratunsk type are developed coincides with the structure of the areas of the Pauzhetka-type hydrothermal systems. Regional tectonics is characterized by comparatively quiet occurrence conditions of the aquifers. Their inclined occurrence can be recorded only over big areas. For instance, the angle of dip of Berezovsk suite in the area of Bolshaia Bannaia hydrothermal system comes to the first degrees. The Viliuchinsk suite in the area of Zhirovaia river has angles of dip not exceeding 10-15°.

Considerable disturbances in the occurrence of sedimentary and volcanic-sedimentary rock masses are observed near young extrusions. Along the contacts with some extrusions the position of the rock masses is badly disturbed. Their angles of dip are different and often come to 80-90°. The role of extrusive domes in the structure formation of the hydrothermal systems of the Banno-Paratunsk type is identical to the role of extrusions in the areas of the hydrothermal systems of the Pauzhetka type.

The Influence of Geological Factors on the Character of Hydrothermal Systems

By the present time researches on certain hydrothermal systems have established the fact that the intensity of heat supply to the systems is of comparable values not only for the hydrothermal area of Kamchatka, but also for other volcanic areas (Kurile Islands, Salvador). In the area of the Geyser Valley (Kamchatka) the mean values of the heat supply intensity of hydrothermal systems amounted to 2.10^3 kcal/sq.km per sec, at Pauzhetka — $1.4.10^3$ kcal/sq.km per sec, on the Upper Zhirovsk thermal field — $1.4.10^3$ kcal/sq.km per sec, on the thermal fields of Kisly and Sanatorny creeks (Kunashir Island, Kurile Islands) — $1.7.10^3$ kcal/sq.km per sec. and in Salvador 10^3 kcal/sq.km per sec (AVERIEV, 1964; DURR, 1961).

As demonstrated by the above given data the order of the intensity values for the heat supply in different hydrothermal systems, even in volcanic areas at great distances from each other, is very similar. A conclusion follows from these data: approximately uniform heat flows approach the different hydrothermal systems.

However, both on the surface of the Earth and at the depth of the hydrothermal systems the temperature of thermal waters varies substantially. Thus, for instance, in the depths of the Pauzhetka hydrothermal system, the water is of a maximum measured temperature of 200°C and maybe even higher, while the water temperature of Sanatorny creek (Kunashir Island) does not even reach 100°. This makes it legitimate to put a question regarding the subsurface causes that affect the nature and temperature regime of the hydrothermal systems.

The most active geological factors affecting the nature of hydrothermal systems are the lithological properties of rocks and the extent of jointing, which characterizes their properties as water collectors; the presence of a water impermeable top horizon of rocks and the tectonics of the area determine the supply conditions of the system and its discharge.

The properties of rocks as collectors determine the rates of water filtration. Under the conditions of a high permeability, great grades, an intense infiltration and a maximum water exchange in the system, when big masses of cold infiltration waters can pass over the area of an abnormal heat flow, there is an active emission of heat towards the stream and its discharge before the water has time to become warmed up and reach high temperatures.

On the contrary, under poor filtration properties of the aquifers or under the conditions of a poor water exchange, which can be explained by the position of the aquifer and by its tectonic conditions, the water in the system can acquire a high temperature.

However, if in the last case, there is no top water-impermeable horizon, the temperatures will not be able to rise above the temperature of saturation under an atmospheric pressure on the level of the water table. In humid areas the temperature regime will change greatly also depending upon the amount of atmospheric precipitation.

This determines exactly the role of the top confining horizon. First of all, it greatly decreases heat losses of the water stream table, and, secondly, there is lesser intensity of the infiltration supply. This creates necessary conditions for the formation of a high-temperature hydrothermal system. It should, however, be added that the formation of a high-temperature hydrothermal system in enclosing rocks with good collector properties is possible under the conditions of a stagnant or semi-stagnant regime. The latter is provided by the *tectonic* factor.

In addition to the enumerated factors in the specific features of the geological structure of the area of active hydrothermal systems the character of the systems is affected by a vast complex of other factors. This means that only a quantitative evaluation of the entire complex of geological factors affecting the formation of present hydrothermal systems can serve as a basis for the theory of the hydrothermal process.

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