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Long-lived Volcanic Centers of Kamchatka Geothermal Areas

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ABSTRACT

The current problems of hydrothermal processes and ore-forming systems are volcanic heat sources and mechanisms of heat transfer. In Pauzhetsky, Semyachik and Mutnovsky geothermal areas in Kamchatka, active long-lived volcanic centers have been studied, with which high-temperature hydrothermal systems are associated. In the Banno-Paratunsky geothermal area the Paleogene and Neogene long-lived volcanic centers were identified, with which low-temperature hydrothermal systems are associated. The geological history of the long-lived volcanic centers development is characterized by changes in their structure as a result of hydrothermal-magmatic activity. These changes are manifested in the generation and evolution of magma chambers in the mantle and in the Earth's crust. Basalt melts of the mantle chambers transport the deep heat to the Earth's surface through plane magmatic channels without significant losses. The heat flow of these volcanic centers is short-lived and is characterized by a significant capacity of ~8,000 kcal/km2s. The long-lived volcanic centers are characterized by the presence of magma chambers in the Earth's crust. They shield the part of the mantle heat flow. Their thermal capacity on the Earth's surface is estimated from 1000 kcal/km2s to 5000 kcal/km2s. It is assumed that a significant amount of thermal energy is retained in the long-lived volcanic centers. It is spent on formation and activity of the chambers as well as the convective hydrothermal ore-forming systems. The evolution of such centers is accompanied by the formation of complexes of metamorphic rocks which interaction with high-temperature mantle melts is accompanied by redox reactions like combustion. As a result of these reactions, thermal energy is produced in such magma chambers. A long-lived jet magmatic system is formed, and it provides the transfer of mantle heat. Heat transfer in the system is accompanied by minimization of heat losses, accumulation of heat and its additional generation which is necessary for the heat transfer in the structures with low thermal conductivity. The formation, evolution and extinction of magma chambers and reservoirs in such heat-conducting structures are controlled by the thermophysical properties of the rocks, their geological structure and redox processes in them.

1. INTRODUCTION

At present, it is believed that the formation of volcanic ridges in the geothermal regions of Kamchatka was a continuation of the evolution of islands-volcanoes in the oceanic ridges structures (Belousov, 1978). Such volcanic islands are characterized by fissure eruptions of basaltic magmas, multichannel volcanic structures and formation of embryos of andesite magmatic chambers in the Earth's crust. As the regimes of the island arc change to the continent, these volcanogenic structures are transformed into hydrothermal-magmatic systems with eruptive centers. They erupted rhyolitic and dacitic magmas of shallow chambers (Henley, Ellis, 1983). According to our research, the eruption of ash and pumice flows and extrusions occurred in the era of glaciation (Belousov, Belousova, 2018). Such hydrothermal-magmatic systems associated with these long-lived volcanic centers are widely developed in the East Kamchatka volcanic belt (Belousov, 1978).

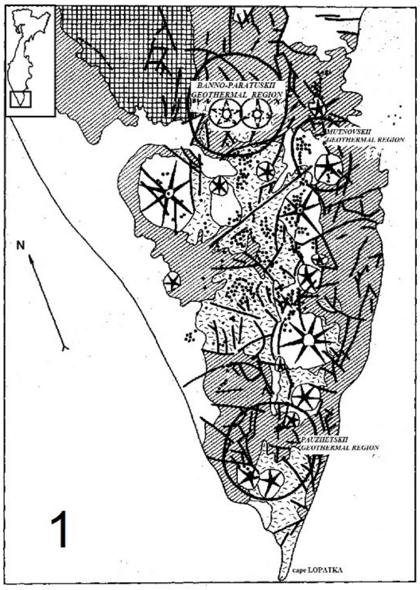
Flat low-power structures are eruptive channels. During cooling down, they are transformed to basalt dikes. Near the surface they converge and concentrate heat transfer. They limit the heat losses, which leads to the thermal insulation of the entire magmatic system from the upper mantle to the Earth's surface. In the upper part of the Earth's crust, as a result of the interaction of mantle melts with surrounding rocks and meteoric water, part of the anomalous convective heat flow in long-lived volcanic centers is spent (from 2000 kcal / km^{2}s to 6000 kcal / km^{2}s, Belousov et al., 2017) for heating of the underground water, formation of magma chambers, metamorphism and formation of ores.

2. GEOLOGY OF GEOTHERMAL AREAS OF KAMCHATKA

Geothermal regions of Kamchatka are located in large troughs of the north-east strike. They are limited either by regional faults with the significant displacement amplitude, or by a series of stepped faults of small amplitude, which are filled with quaternary volcanogenic and volcanogenic-sedimentary rocks (Ehrlich, 1973). Geological and structural positions of geothermal areas are illustrated by geological schemes (Fig. 1, 2).

In this regard, we have identified two groups of geothermal areas: 1- regions in the young structural-facial zones of volcanic areas composed mainly of volcanic-sedimentary formations of Pliocene-Quaternary age; 2 - regions in the structural-facies zones composed mainly of dislocated sedimentary and volcanogenic-sedimentary formations of Mesozoic and Paleogene-Neogene age.

The first group includes Pauzhetsky and Semyakchiksky geothermal regions. Thermal manifestations in the Pauzhetsky and Semyachik geothermal regions are confined to volcanotectonic uplifts or ring structures. As a rule, steam jets are located in the summit part of volcanotectonic uplifts. Thermal waters are unloaded at their feet. The formation of ring structures is accompanied by the manifestation of acid volcanism in the form of extrusions of dacite-rhyolite composition and eruptions of an acidic pyroclastic material (pumice, ignimbrites, etc.). Young (Quaternary) sequences of relatively loose pyroclasts and their erosion products, filling in the depressions, have a thickness of 1 km or more. Their good reservoir properties create the preconditions for the formation of reservoir accumulations of thermal waters in these deposits.



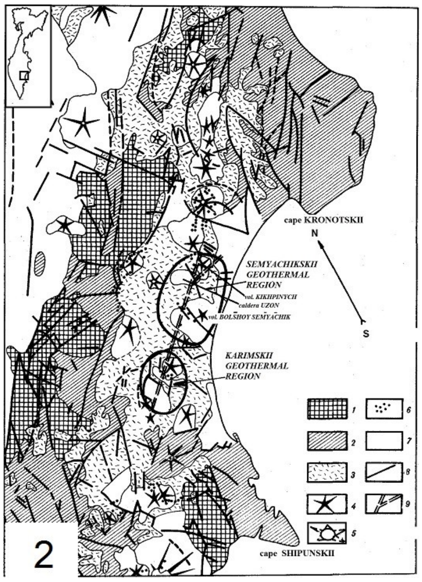


Fig. 1. Geological sites of Banno-Paratunsky, Mutnovsky and Pauzhetsky geothermal regions.

Fig. 2. Geological sites of Semyachik geothermal region. (Belousov, 1978): 1 - rocks of the Cretaceous basement; 2 - rocks of Paleogene-Neogene age; 3-volcanogenic and volcanogenic-sedimentary rocks of the Pleistocene-Holocene; 4 - stratovolcanoes; 5 - volcanoes of the Banno-Paratunsky geothermal region; 6 - eruptions and basalt effusions of areal type; 6 - coastal and lake sediments; 7 - faults; 8 - direction of the deep tectono-magmatic fault in the Semyachik geothermal area

The geothermal regions of the second group include Mutnovsky and Banno-Paratunsky regions. The thickness of the formations composing the geothermal regions of this group is measured in hundreds of meters, reaching tens of kilometers in some places. In most cases volcanogenic-sedimentary formations of Paleogene-Neogene age were previously exposed to high-temperature waters. The processes of modern metamorphism are overhead. Among the hydrothermal changes in the rocks, propilization is most common. These processes significantly influenced the filtration properties of rocks. In the early stages of development of the region, the rocks had porous permeability which subsequently disappeared under the influence of their hydrothermal change. As a result of diagenesis and tectonic movements, the strata were disturbed by a dense network of shrinkage cracks and crushing zones. The tectonics of these regions is characterized by intense dislocations. In the Banno-Paratunsky geothermal area, two lines of thermal springs are outlined: one stretches along the left side of the Paratunka River valley (Nizhneparatunsky, Sredneparatunsky and Karymchinsky sources); another in the west is the line of the Nachikinsky, Bolshe-Banynyh, Malo-Banynyh and Karymshinsky thermal springs.

Volcanogenic-sedimentary rock complexes compose the lower structural layer and play the role of water-bearing strata. The middle structural layer is represented mainly by young or recent volcanogenic formations from basalts to rhyolites. Acid and andesitic volcanism manifests itself in the form of extrusions and extrusive massifs. The latter form watersheds and have the outlines of regular cones, obelisks, ridges, irregularly shaped arrays, domes or rows of domes. Basaltic volcanism manifests itself in the form of isolated monogenic formations with small lava flows. Slag cones are located at their sources. The upper structural layer consists of loose or weakly compacted deposits filling structural depressions. They are represented by marine, glacial, fluvioglacial, and alluvial sediments of various granulometric composition - from sludge to boulders. The capacity of this layer in some places reaches 200 m.

In the geological sections of the Banno-Paratunsky geothermal area, there are also welded tuffs and ignimbrites, known as deposits of the Berezovsky Formation. The formation is located in the depression between the remnants of the edifices of inactive andesite-basalt stratovolcanoes and long-lived volcanic centers. It is composed mainly of ignimbrites and rhyolites breaking them by extrusions. The age of acidic tuffs and ignimbrites is Eopleisocene, and the age of rhyolitic extrusions is 0.5–0.8 million years (Sheymovich and Golovina, 2003). They are not characterized by strong acid changes, as it is observed in extrusions of the long-lived volcanic centers of the Semyachik and Pauzhetsky geothermal areas. However, the presence of ore vein deposits is noted (Rogozin, 2009). A large area is occupied by Berezovsky ignimbrites (more than 1000 km^2). Their significant capacities suggest that in the Banno-Paratunsky geothermal area center-type ignimbritic volcanism is of an areal character.

3. GEOLOGY OF LONG-LIVING VOLCANIC CENTERS

Earlier in the description of the geological structure of Kamchatka geothermal areas, long-lived volcanic centers were mentionsd: in the Pauzhetsky geothermal area - Kambalny, Koshelevsky; in Semyachik geothermal area - Kikhpinychsky, Zubchatka, Bourdy, Uzon; in Mutnovsky geothermal area – Mutnovsky, and in Banno-Paratunsky geothermal area - Paleogene-Neogene long-lived volcanic centers Karymshinsky and Goryachaya hills (Bolshaya-Bannaya hydrothermal system) (Belousov, 1978).

One of the main structural features of long-lived volcanic centers associated with hydrothermal systems is the absence of a permanent fixed eruption channel. Throughout the history of their development, especially in the latter stages, in subaerial and ground conditions, the long-lived volcanic centers in geothermal areas have been characterized by the migration of eruption centers.

At the sites where long-lived volcanic center joined with the structure of the adjacent hydrothermal system, the intrusion of large masses of viscous lava of daciori-rhyolite composition in the form of extrusive domes occurred.

3.1. Kambalny long-lived volcanic center of the Pauzhetsky geothermal area

The study of the Kambalny long-lived volcanic center (since the 1950s) allowed us to determine the rock complexes that form the Pauzhetsky geothermal area - their age relationships, regional and local structures. The theory of the evolution of Southern Kamchatka was proposed (Belousov, 1978).

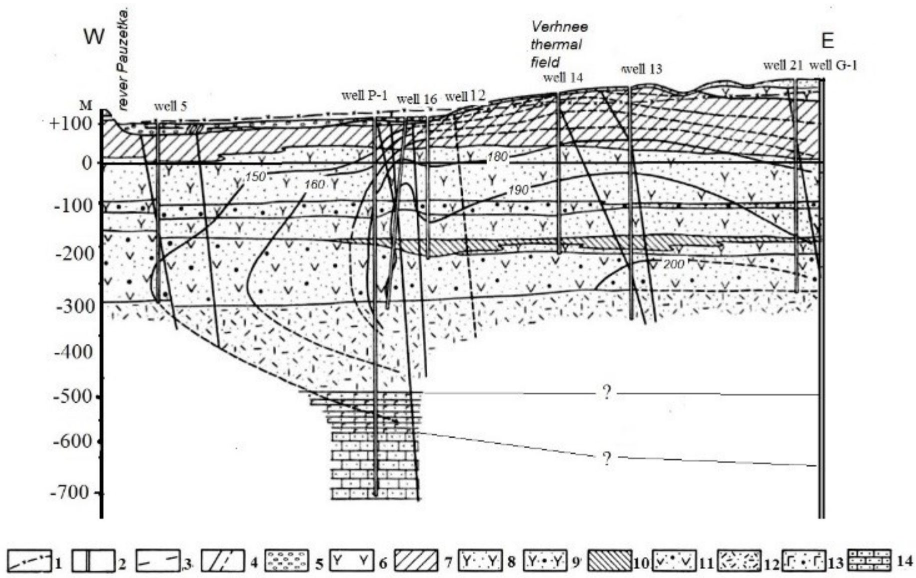


Fig.3. Geological-hydrological section of the Pauzhetsky deposit of thermal waters. 1 - piezometric level of thermal waters; 2- exploration wells; 3 - geoisoterms; 4 - tectonic faults: discovered and assumed; 5 - alluvium; 6 - lava and lavobrekchii of andesite-dacite; dacite tuffs; 8 – dacites tuffs; 9 - tuffbreccia; 10 - mixed tuffs; 11- tuffbreccia of andesites; 12 - litho-crystalline silicificated tuffs of dacites ("in situ ignimbrite"); 13 - basalt tuffs and tuffbreccias; 14 - sandstone.

The rocks of the region are of volcanic and volcanogenic-sedimentary origin. The depth of GK-1 is 1150 m. Several wells crossed the horizon of lithocrystalline tuffs (Fig. 3). The first researchers (Pauzhetsky hot waters in Kamchatka, 1965) identified them as analogues of the ignimbrite of the Wairakei hydrothermal system in New Zealand. The petrographic characteristics of these rocks in the Pauzhetskoye field are more complete (Pauzhetsky hot waters in Kamchatka, 1965), since well drilling at Pauzhetka was carried out with full coring.

Quartz is found in the form of debris, often melted, corroded and crushed. Crystals are transparent without wavy extinction. Sometimes they contain bubbles and small inclusions of glass, the content of which reaches 15%. The hornblende pleochroates from greenish yellow to brownish yellow. Its quantity does not exceed 7%. The augite content is also about 7%. Ore minerals are magnetite and ilmenite.

Fragments of rocks have a basalt composition. The pumice, andesite, and dacite debris of the svitrofiroi and microlite structure of the main mass of phenocrysts of plagioclase, hornblende and pyroxene are widespread. The role of cement is played by a colorless glass with small acute-angled fragments of quartz and less often plagioclase. In many areas, the glass is crystalline and has a microspherolite texture. Fragments of lavas and minerals are melted, corroded by glass, and often have fuzzy boundaries.

In these tuffs of dacite composition there are fragments of andesite and andesite-basalt. Their quantity at the base of the stratum increases and the rock goes into the andesite-basalt tuffbreccia composition, which Averyev V.V. and Belousov V.I. unite with litho-vitro-clastic tuffs. The reason for this is the observations in natural outcrops, where the litho-vitro-clastic tuffs are gradually saturated with fragments of andesites and anzhezto-basalt and the stratum turns into tuffbreccia. Cements of tuffbreccia and caked tuffs have a similar composition.

Later Belousov V.I. (1978) showed that lithocrystalloclatic tuffs were cemented by metacolloid silica, zeolites, and hydromica of hydrothermal origin. In this horizon, a stream of high-thermal waters of the underwater hydrothermal-magmatic system was localized. Mixing these waters containing silicagel with seawater (cold, containing Mg) was accompanied by the formation of amorphous silica and other hydrothermal minerals in the pore space (Iler, 1982). The rock became monolithic, impermeable to water, with an increased amount of SiO_2 (average content - about 60%). This process led to the geochemical isolation of the hydrothermal-magmatic system of the Thermalny Volcano.

3.1.1. Extrusions.

Young extrusions of rhyolite and andesite-dacite composition are widely developed on the Thermalny Volcano and on its periphery. They date from the Upper Pleistocene and Holocene and occupy a significant part of the long-lived center. Their sizes range from 0.01 to 8 km^2. Small extrusions are dome shaped. They are usually surrounded by tuff deposits which dip to the sides of the dome and are disturbed by faults with small displacements.

Larger extrusions produce more significant disturbances in the surrounding tuffs. In terms of extrusion, Sopka Ploskaya volcano has an isometric shape. The area of the dome is 4.7 km^2, the elevation difference is about 700 m. Two lava flows are connected with the dome. The total length of the streams is 2.5–3.0 km, thickness is from 30 to 150 m. Zonality is observed in the structure of the dome due to the textural characteristics of the underlying rocks. The southwestern part of the dome top consists of pumice-like rhyodacites, which at the upper edge of the obelisks are replaced by glassy species with inclusions of spherulites.

3.1.2. Hydrothermal changes.

The axial part of the hydrothermal flow of the Pauzhetskaya system is controlled by the deposition of lomontite, which is a mineral characteristic of low-temperature propylites. A sharp decrease in the rate of thermal filtration of water in impermeable horizons leads to paragenesis of lomonite and calcite + hydromica. Quartz areas consist of crystalline chalcedony and mosaic-quartz aggregates. At the depths of 25–80 m and 125–150 m, complete silicification is observed. Quartz-adular metasomatites are also widely developed at different depths. Thickness of the zones is from tens of meters to centimeters.

The rhyolites of the extrusion apical part in the center of the Thermalny volcano caldera are changed to opals with a small amount of alunite.

3.2. Kikhpinychsky long-lived volcanic center of the Semyachik geothermal area

In the early stages of geological and structural studies, the relationship between the Geysernaya hydrothermal system and the Kikhpinychsky long-lived volcanic center was not considered (Beloussov, 1967). In recent years, detailed studies have been carried out to study the geological structure of the Geysernaya hydrothermal system and the volcanic structures adjacent to it (Belousov, Belousova, 2018).

The Kikhpinychsky long-lived volcanic center is located in the northeast sector of the Semyachik geothermal area in the upper reaches of the Geysernaya River, to which the well-known geysers of Kamchatka are confined (Belousov, Belousova, 2018). The geological structure of the Kikhpinychsky long-lived volcanic center differs from the geological structure of the deep tectono-magmatic fault by a more concentrated location of eruption centers per unit area. The occurrence of basalt dykes, which served as drains for the incoming material and heat in erosion incisions near the supposed top of the ancient apparatus of the stratovolcano Kikhpinich is much more than in the zone of deep fault. The eruption centers of the Holocene age are located along the long axis of the ellipse of the cross-section of the Kikhpinychsky long-lived volcanic center. Basalt dikes near the summit of the ancient Kikhpinich cone are fan-shaped, which confirms the presence of a single eruption center. The volume of erupted material from this center is much higher than the volume of material in eruption centers related structurally to a deep tectonomagmatic fault. In the Pleistocene-Holocene time, the Kikhpinychsky long-lived volcanic center is characterized by eruptions from several eruptive centers and the distribution of thermal unloading over a large area covering the northeastern and southern slopes of an ancient volcano. The evolution of a magma chamber in the upper part of the Kikhpinychsky long-lived volcanic center is described in detail in the work of Belousov and Belousova (2018).

3.3. Long-lived volcanic centers of the Banno-Paratunsky geothermal area

The long-lived volcanic centers of the Banno-Paratunsky geothermal area are represented by the Upper Miocene-Pliocene complex of rocks exposed in the basins of the Paratunka, Karymchina and Olkhovaya rivers. They form the arrays of Tolstii Mis, Shemedogan, Shapochka, Sopka Goryachaya, Vachkazhech and others and are the remnants of ancient stratovolcanoes. In all the more ancient sediments, they are deposited with angular unconformity. Rocks are represented by basalts, andesite-basalts, andesites and their tuffs. Almost in all sections of the series pyroclastic deposits predominate. The accumulation of sediments took place in subaerial conditions. Their maximum thickness, determined by a series of cuts, does not exceed 500-600 m.

Hydrothermal systems are located on the diping slopes of the edifices of these volcanoes, which are broken by faults. There was a lowering of the blocks. At present, these sites are river valleys and are filled with loose continental sediments. The slopes of the buildings are broken by extrusions of rhyodacite composition of the Quaternary age. The sites of discharge of the hydrothermal systems of the Banno-Paratunsky geothermal area are located in the river valleys and are closely associated with the modern river network. Thermal manifestations on or near young extrusions are absent with rare exceptions.

Water-bearing rocks are represented by a complex of highly fractured and waterproof rocks of the Paleogene-Neogene age. The nature of filtration is fracture-vein. As a rule, the formation of low-temperature hydrothermal minerals in the overlying loose sediments occurs at the discharge site. Porous rocks filled with metacolloid quartz become impermeable to water. This process leads to a gradual waterproofing of the place of discharge of thermal water. By drilling a large number of wells in the valleys of the Paratunka and Bannaya rivers, the local distribution of thermal waters and their association with young extrusive formations were established.

Analysis of the development of volcanism in the Banno-Paratunsky geothermal area allows us to conclude the following. During the Paleogene-Neogene period and the entire Quaternary stage this region was characterized by the development of areal effusions. In the adjacent areas, where there are outcrops of the Cretaceous basement (Nizhnekarymchinskaya volcanic zone), areal basaltic volcanism prevails. The manifestations of acidic volcanism can be observed there. Areal acidic volcanism with rare manifestations of basaltic volcanism in the form of monogenic scoria volcanoes prevails in the structures composed mainly of Paleogene-Neogene volcanogenic-sedimentary strata. The thermal manifestations of the Banno-Paratunsky geothermal area are closely related to them. On the remnants of these volcanic structures there are no steam-gas thermal manifestations. We refer them to the long-lived volcanic centers that are at the stage of complete disintegration. However, at present, the nature of volcanism in the Quaternary time allows us to suggest an existence of the abnormal heat flow during a long period of time. Numerous eruptive centers are located along the lines parallel to the strike of the East Kamchatka volcanic zone.

4. DISCUSSION

The origin of heat energy controlling magmatism and hydrothermal activity remains one of the main problems of geology. Nowadays, the dominant point of view is that the source of heat in the hydrothermal process is magma. In the second half of the twentieth century, when the study of thermal waters in the areas of modern volcanism acquired an industrial scale, quantitative estimates of the thermal capacity of modern hydrothermal systems were needed. It turned out that the energy of the hydrothermal process is comparable to the heat loss of crust magmatism (Averyev, 1966; Belousov, Sugrobov, 1976). In this regard, the model of thermal power supply of modern hydrothermal systems included the influx of heat from the levels of the upper mantle. It was assumed that the heat transfer agents were transmagmatic volatile compounds and, mainly, water.

4.1. General information about the long-lived volcanic centers

The thermal imbalance of magmatism and hydrothermal activity in some areas of modern volcanism is forcing researchers to look for a new explanation for the occurrence and functioning of heat sources in hydrothermal-magmatic structures. For example, Belousov et al. (1971) presented the estimates of heat removal by thermal waters, acidic and basalt magmas in some hydrothermal-magmatic systems of Southern Kamchatka. During this period, volcanic activity had an areal character, and the island arc which existed in this place for several tens of millions of years became the continental structure of the southern tip of the Kamchatka Peninsula. In recent years, in the study of areas of modern and young volcanism, much attention has been paid to the study of voluminous acid pyroclastic formations associated with calderas of various origins. The "sudden" appearance of large reservoirs of acid magmas is associated with a change in the island volcanic arc regime to a continental regime (Belousov, 1978). The abrupt transition to eruptions of acid melts in the transition zone from the arc to the continent is difficult to explain by the inertial process of crystallization differentiation, which is complicated by forced convection caused by injections of basalt melts. In our opinion, the energetics of mantle melts and water in them cannot ensure the heating and melting of the host rocks and the groundwater filtered in them. Therefore, for the formation and long-term activity of hydrothermal-magmatic systems, a sufficiently powerful source of thermal energy is necessary. It is assumed that such a source is a magma chamber in the upper part of the long-lived volcanic centers. This is a chemical reactor that produces heat. Excessive degassing of stratovolcanoes with magmatic chamber in the Earth's crust confirms our assumption that thermal energy is generated in these chambers due to redox reactions (Shinohara, 2008).

4.2. Magmatic chambers in the Earth's crust: their formation and role in the long-lived volcanic centers

The study of underwater hydrothermal-magmatic convective systems in the 1970s showed that they form massive sulphide deposits. They reach volumes of tens of millions of tons of sulphide mass which is closely associated with the deposition of various forms of quartz (Bogdanov, 1997). This process in space and time is associated with frequent injections of high-temperature mantle melts. Siliceous rocks with deposits of massive sulphides or thick patches of iron sulphides may fall into the zone of influence of high-temperature magmas. The composition of amorphous silica contains ion-hydroxyl and bound water. When exposed to the thermal field of magmatic melts, they should be separated from the molecules of silicic acid and at high temperatures will undergo a process of dissociation. As a result, atomic oxygen and hydrogen are formed. They react with sulfides (Nekrasov, 1973, p.399).

$$3FeS + 10H_2O = Fe_3O_4 + 3SO_2 + 10H_2$$

$$4FeS_2 + 11O_2 = 2Fe_2O_3 + 8SO_2 + 790 \text{ kkcal}$$

The temperature at which these reactions occur is approximately 800°C. It is possible at the contact of sulphides and basalt magma. This reaction produces 800 kcal and occurs in the burning mode. Thus, the calorific value of pyrite is about 2000 kcal/kg. During the combustion of 1 kg of pyrite, sufficient heat is released to melt 8-9 kg of rock from 0°C to 800-900°C with a heat capacity of about 300 kcal/kg.

During the evolution of long-lived volcanic centers, the sulphide-siliceous complex is constantly generated and is a convenient medium for andesitic, dacitic and rhyolitic melts. The likelihood of such a process was indicated by Gudmundsson (1995). The significant factor contributing to the development of the melting process can be high silica contents in the original rock and other additives, including highly volatile chemical elements. They play the role of fluxes that lower the melting point of the original rocks. Their action is well studied in metallurgy.

The second important position in the proposed hypothesis is the established fact of the generation in large volumes of organic matter and prebiological compounds near the sources of discharge of underwater hydrotherms, the reproduction of which is estimated at millions of tons per year. A zone of chemical and microbiological oxidation of reduced gases is functioning near the underwater hydrothermal-magmatic systems. The processes occurring in this zone change the oceanic crust and lead to the formation of argillites. They act as screens that promote the accumulation of both heat and natural gas (Thorseth et, al., 1995; Behar et, al., 1995). These structures can also be exposed to magmatic melts, ignite and complement the heat balance of the long-lived volcanic centers.

4.3. The role of basalt dikes in the long-lived volcanic centers

As a result of studies of long-lived volcanic centers associated with modern hydrothermal systems, there is an indication to a wide development of basalt dykes. In connection with these data, it seems to us that in the long-lived volcanic centers participating in the formation of modern hydrothermal systems, a dyke is the main structure through which melt and heat transfer occurs. A small amount of magma and a large heat loss surface of a flat magmatic channel cause high values of the temperature head controlling the transfer of heat throughout the entire magmatic system, including magmatic reservoirs. Magmatic melt is a multicomponent system, the elements of which differ in thermo-physical parameters. In this regard, a significant proportion of thermal energy is transferred by mobile elements (trans-magmatic fluids). Trans-magmatic fluids (gases and alkali metals) under the action of a large temperature head as a result of thermal diffusion should be concentrated in the head part of the eruptive melt (Belousov, Belousova, 2016). This process leads to the melting of even refractory host rocks, such as basalt lava. Thus, it is assumed that small igneous bodies such as dykes are elementary structures that play the role of magmatic melt drains and transport large amounts of thermal energy in the crustal environment.

4.4. Hydrothermal Metamorphism and Large-Volume Acid Magma Generation

At present, the hypothesis of a catastrophic eruption of a “supervolcano” in the Banno-Paratunsky geothermal area has been widely adopted in publications (Leonov, Ragozin, 2007). The basis for this concept is some data on the formation of a powerful stratum of acidic and ultra-acidic rocks, which is known as the Karymshinsky volcanic complex. It is represented by acidic tuffs and ignimbrites and numerous subvolcanic bodies, which are located in a volcanotectonic depression. Sheimovich and Khatskina (1996) did not regard it as a caldera, but assumed that the rocks of the Karymshinsky complex were formed as a result of the manifestation of areal extrusive volcanism.

The nature of eruptions of rhyolite extrusion Sunduk (Yaschik, Belousov, 1978) in the Middle Pleistocene indicates that the formation of ignimbrites that anticipated the emergence of an obelisk of the mesa type (similar to Tuay in Iceland) occurred in the form of a relatively quiet "effusion" of pyroclastic flow. It is assumed that this type of eruption of ignimbrites and acid melts, which dominated the geothermal region described, is due to the presence of glaciers. They put pressure on the horizons of partial melting. Therefore, the concept of "supervolcano" which formed a thick mass of acidic rocks (more than 800 km^3) is probably unrealistic.

We offer a different view on the origin of such acid rocks. It is based on the concept of the role of hydrothermal metamorphism in the depths of long-lived volcanic centers (Belousov, Belousova, 2018, 2019).

The thermal waters of the Bolshe-Bannaya hydrothermal system are characterized by a high content of carbon dioxide. It influences their dynamics and chemo-metamorphic processes. Rocks that were drilled on the thermal field of the Bolshe-Bannaya hydrothermal system contained a significant amount of amorphous silica and quartz to a depth of several hundred meters. It is assumed that the silicification of the rocks of the upper part of the stratum near the volcanic andesite-basaltic construction of Gora Goryachaya is due to the boiling of the medium- and low-temperature thermal waters of the Bolshe-Bannaya hydrothermal system. The depth of boiling (2.2 km) of such relatively low-temperature hydrothermal solutions is determined by the high concentration of CO_2 in their composition. This process is accompanied by the formation of water vapor. As a result, there is a large loss of heat and sedimentation of dissolved silica. Its content in the water of the Bolshe-Bannaya sources is 300 mg/kg at a temperature of about 100°C. In accordance with the graph of the solubility of amorphous silica, the concentration of silicic acid in thermal water at a temperature of 168°C reaches 800 mg/kg. Thus, 500 mg of SiO_2 can be precipitated from 1 kg of thermal water in water-bearing rocks. At higher temperatures at great depths, the silicification process is more intense.

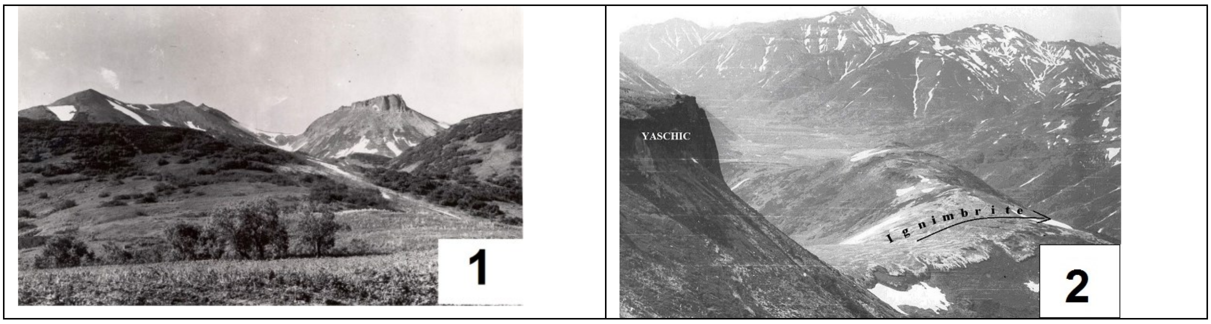


Fig. 4. Table Mountain - Extrusion Sunduk and its flow of ignimbrites. Banno-Paratunsky geothermal area. Kamchatka 1. General view of the mesa (extrusion of the Sunduk); 2. In the foreground, an obelisk of extrusion Sunduk, in the center - a pyroclastic flow (welded rhyodacite tuff).

The carbonated thermal waters of the Banno-Paratunsky geothermal area are widespread at a considerable distance (Malkinsky and Nachikinsky thermal fields). It is assumed that the source of carbon dioxide are magmatic chambers in the Earth's crust of these volcanoes and basalt magmas of areal volcanism, which roots reach mantle magmatic reservoirs. During maximum activity of the Banno-Paratunsky area, several stratovolcanoes and long-lived volcanic centers were located within its boundaries. The hydrothermal systems similar to the Geysernaya hydrothermal system in the Kikhpinychsky long-lived volcanic center were associated with them. The evolution of these volcanogenic structures was accompanied by differentiated tectonic movements. As a result, a closed depression arose and an artesian hydrothermal basin was formed, from which the flow of thermal water was severely restricted. It was filled with high-temperature waters saturated with silica gel. Heat release by this hydrothermal system occurred in the form of gases (mainly CO_2) with water vapor. As a result of underground boiling, the deposition of minerals and the formation of horizons of silicified rocks with the properties of heat insulators (cap-rock) occurred. During the Middle Pleistocene glaciation, a similar role was played by thickness glaciers (Belousov, Belousova, 2018). The formation of cap-rock horizons was accompanied by both an increase in temperature and an increase in gas concentrations. High concentrations of CO_2 formed carbonic hydrothermal solutions with high contents of Ca-silica gel. It adsorbed metals and was transformed into ore-bearing fluid (Belousov, Belousova, 2019). Accumulation of heat led to a significant increase in temperature under the glaciers and cap-rock horizons. As a result, both sintering and melting occurred. Ignimbrites and lenses of acid melts were formed. Plastic acid melts influenced by the pressure of glaciers and enclosing rocks were squeezed up and deformed the horizons of ignimbrites and host rocks. The rifts and cracks around such uplifts served as channels through which boiling and degassing underlying ore-bearing carbonic fluids rose. As a result of this process, quartz-carbonate ore veins were formed (Rogozin, 2009). Catastrophic eruptions did not occur. No significant migration occurred. Therefore, we proposed to call such ignimbrites *in situ*.

5. THE MODEL OF EVOLUTION OF THE LONG-LIVING VOLCANIC CENTERS

The generalization of the geological history of the development of the long-lived volcanic centers in the Kamchatka geothermal regions makes it possible to consider a scheme of the interrelationships of the processes occurring over the long history of the formation, activity and extinction of such a structure.

The initial stage of the evolution of the long-lived volcanic centers in the geothermal regions of Kamchatka is associated with the development of the island volcanic arc. The eruption of mantle melts of basalt composition occurred in the subaerial conditions of the islands archipelago.

The destroyed material coming from the levels of the upper mantle was subjected to mechanical and chemical differentiation and was distributed near the long-lived volcanic centers. In the structure of the long-lived volcanic centers the conditions arose for the formation of rocks that could isolate heat. Thermal energy accumulation and partial melting of host rocks occur in these places. If such host rocks contain sulphides or carbon compounds, then an additional amount of heat is produced as a result of redox reactions. This process causes long-term activity of the long-lived volcanic centers. A schematic geological section of a high-temperature hydrothermal system and a long-lived volcanic center is given in the article by Belousov and Belousova (2018).

A special stage in the development of the long-lived volcanic centers of the geothermal regions of Kamchatka begins in the Pleistocene. Lava material significantly predominates over the volcanogenic-sedimentary, both in sections and in area. Lava flows spread far from the centers of eruptions. During this period of the development of the long-lived volcanic center, there is no direct contact with the sea. As a result, the nature of the eruption is changing. Explosions give way to effusive and extrusive activity. Erosion processes in continental conditions occur at a slower rate than in marine conditions. With the material feed rate remaining unchanged, the structure of the surface part of the long-lived volcanic center changes. There is a sharp increase in the size of volcanic islands. This facilitates the penetration of magmatic melts to the surface of the Earth. The conditions of heat transfer are sharply replaced by a decrease in heat losses both in near-surface conditions and in the depths of a long-lived volcanic center. During the Pleistocene glaciation in the long-lived volcanic centers of Kamchatka, magma chambers expanded into the Earth's crust due to limited groundwater runoff, an increase in temperature of water-bearing rocks in the upper part of hydrothermal systems, partial melting of silicified rocks and formation of ignimbrites (Belousov, Belousova, 2018). It is assumed that thick glaciers and surrounding host rocks exert pressure on the warmer parts of the partial melting zones. As a result, the melt is squeezed up to the surface of the Earth and the formation of domes, which are preceded by emissions of the sintered material, occured. The general heating of the subsoil facilitates the emergence of multiple eruption centers within the long-lived volcanic center. A large number of monogenic and polygenic apparatuses are formed. Feed channels break through tuff-sedimentary strata of the basement of volcanic structures. Dykes, which during their formation often played the role of the feeding channels of volcanoes, have the properties of thermal drains, transporting significant amounts of magmatic melt and heat to the surface of the Earth. To create a thermal field in tuff-sedimentary strata with a particularly high temperature, there must be certain conditions that contribute to the accumulation of heat. This is a stagnant regime of water in tuff-sedimentary strata and limited supply of groundwater by infiltration of meteoric waters, as well as the presence of a heat-insulating upper horizon. The introduction of a magmatic melt into the long-lived volcanic center occurs periodically. However, the impulsive nature of the transfer of material and heat in the volcanic process, when melt is introduced into the strata of tuff-sedimentary rocks, is replaced by intrusive and hydrothermal processes, in which thermal energy is dissipated evenly. Therefore, the pulsating nature of the supply of material and heat in the deep horizons of modern hydrothermal systems is weakly manifested near surface conditions.

The probable time of the laying of the long-lived volcanic centers is determined by the general development of a specific area of the Earth's crust on which the underwater volcanic ridge is formed. It is assumed that this is due to the interaction of complex rocks formed in underwater-marine hydrothermal systems (sulphide-silica composition) and basalt melts. As a result of this process, an excessive amount of heat is generated, which supports the combustion reaction. An embryo of a magma chamber is formed in the Earth's crust. It maintains the magmatic system of the long-lived volcanic center.

The last stages of the development of these centers are characterized by their complete decentralization. Thus, the long-lived volcanic centers die off at some stage of their activity.

6. CONCLUSION

The formation and life expectancy of long-lived volcanic centers are due to the origin and functioning of magma chambers in the Earth's crust. These centers are located in volcanic zones.

Long-lived volcanic centers are active geological structures in modern volcanic areas. They are formed by abnormal heat fluxes that originate in the upper mantle of the Earth. They are transported through the earth's crust by hydrothermal-magmatic systems to the surface of the Earth and further down to Cosmos. They are controlled by the processes of heat balance according to the laws of heat transfer and temperature pressure. These processes determine the mode of heat exchange with the environment, protecting the hydrothermal-magmatic system from excessive heat loss. In this regard, the geological and structural evolution of long-lived volcanic centers does not imply the accumulation of thermal energy in the earth's crust (heat losses) in the amount necessary for the formation of huge magmatic magma and supervolcano reservoirs.

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