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The Role of the Artesian Hydrothermal Systems in the Formation of Large-volume Acidic Rocks in the Geothermal Regions of Kamchatka

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ABSTRACT

The formation of large volumes of rocks of acid volcanism is an important process in the geothermal regions of Kamchatka. Currently, the hypothesis of a catastrophic eruption of a "supervolcano" in the Banno-Paratunsky geothermal area has become widespread. The basis for this concept is some data on the formation of a thick stratum of acidic and ultra-acidic rocks, which is known as the Karymshinsky volcanic complex. It is located in the volcano-tectonic depression. Caldera not found. There are no signs of the movement of acidic products of a powerful explosion (~ 275 km^3). It is assumed, that the internal energy of acidic magmas in this region is insufficient for the formation of such a mass of eruption products. In this regard, it is assumed that this concept is not sufficiently substantiated.

Recently, evidence has appeared that large-scale ignimbrites and rhyolites are formed from metamorphic rocks. In this regard, we propose a new concept of their formation, based on the role of hydrothermal metamorphism in the bowels of artesian hydrothermal systems. These systems are located in depressions between long-lived volcanic centers. As a result of the discharge of high-temperature groundwater flows with silica gel in depression, a siliceous layer is formed with a thickness of 1-2 km. It plays the role of an upper waterproof horizon with the properties of a heat insulator (cap rock). During periods of glaciation, such depressions are accumulators of powerful glaciers. They complemented the action of cap rock.

The formation of cap rock horizons was accompanied by both an increase in temperature and an increase in gas concentrations (CO_2, CH_4, H_2, and others). The transformation of siliceous strata of cap-rock into ignimbrites, welded tuffs and acid melts of acid composition took place. Under the influence of the weight of glaciers and surrounding rocks, these plastic formations gradually rose up until they appeared on the surface in the form of extrusions and flows of welded tuffs (ignimbrites).

1. INTRODUCTION

The formation of acidic melts is a significant problem in understanding magmatic processes since the bimodality of volcanic products was established (Bunsen, 1851). The disproportion of the volumes of basaltic and acidic volcanic complexes in comparison with rocks of the andesitic composition is known as the Bunsen-Daly gap (Bunsen, 1851; Daly, 1925).

In the geothermal regions of Kamchatka, the studies of the relationships between acid volcanism and hydrothermal activity are conducted (Averiev, 1967; Belousov, 1978; Belousov and Ivanov, 1967; Belousov and Belousova, 2018; Belousov et al., 1983; Belousov et al., 2020; Leonov and Grib, 2002).

Almost all the studied geothermal areas of Kamchatka are located in the East Kamchatka volcanic zone (Belousov et al., 2020). When typing the geological positions of geothermal areas, we use the age principle which allows us to determine the state of water-bearing complexes and water-resistant horizons affecting the dynamics of the thermal water, distribution and maximum temperatures in the upper parts of geological structures. In this regard, we distinguished two groups of geothermal regions (Belousov, 1978).

1. Regions located in the young structural-facial zones of volcanic regions and composed mainly of volcanic-sedimentary formations of the Pliocene-Quaternary age.

2. Areas localized in structural-facial zones composed mainly of dislocated sedimentary and volcanogenic-sedimentary formations of the Mesozoic and Paleogene-Neogene age.

Both types of these geological and geothermal structures with extensive occurrences of acid volcanism and modern artesian thermal water basins are located in the South Kamchatka. Such examples are Pauzhetsky and Banno-Paratunsky geothermal areas (Fig. 1).

2. PAUZHETSKY GEOTHERMAL REGION

2.1 The Geological Structure of the Pauzhetsky Geothermal Region

In the Pauzhetsky geothermal region, the development of the Earth's crust from the Pliocene to the present is due to the evolution of long-lived volcanic centers in the island arc which was the northern continuation of the Kuril volcanic belt. Near their borders the fascial transitions from basaltic lavas and pyroclastic rocks to coarse sediments are observed. These coarse sediments are replaced by increasingly finely fragmented volcanogenic material as the distance from them increases.

From the Upper Pliocene to the Middle Pleistocene, the distribution zone of the effusive basalt composition of long-lived volcanic centers increases sharply. There were a significant number of eruptive channels through which lavas and pyroclastic deposits of various compositions erupted, including ignimbrites, pumice and lava, as well as domes of andesites, dacites and rhyolites. Acidic rocks are products of magma chambers in the Earth's crust. There is an increase in land area due to the appearance of stratovolcanoes with calderas under conditions of glaciation.

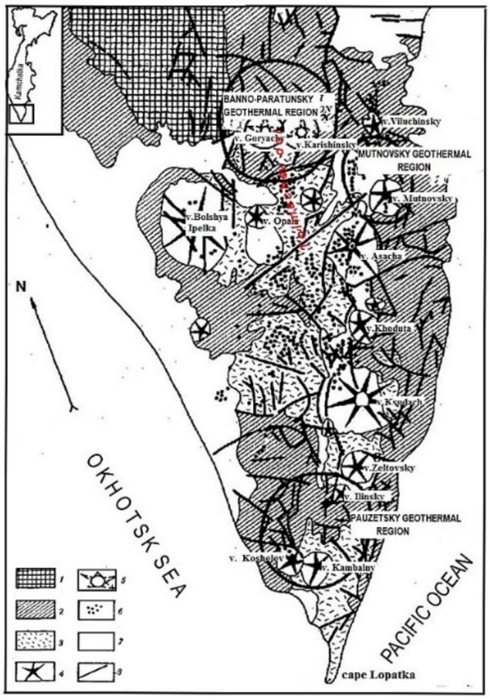

Figure 1: Geological positions of Banno-Paratunsky, Mutnovsky and Pauzhetsky geothermal region. 1 - rocks of the Cretaceous foundation; 2 - rocks of the Paleogene-Neogene age; 3-volcanogenic and volcanic-sedimentary rocks of the Pleistocene-Holocene; 4 - stratovolcanoes; 5 - volcanoes of the Banno-Paratunsky geothermal region; 6 - eruptions and basalt outflows of the areal type; 6 - coastal and lake deposits; 7 – faults.

The Pauzhetsky geothermal region was formed almost exclusively by volcanic processes in subaerial conditions. They were, largely, controlled by climatic conditions. Climate changes have a significant impact on fluctuations in the water regime, both in the marine area and in the underground hydrosphere. The interaction of surface waters and products of magmatism was manifested in the formation of a relief, including high mountains, in connection with which the migration of the snow line and the accumulation of solid perennial meteor showers changed. Obviously, such structures had a significant effect on the temperature regime in volcanic structures and underground hydrosphere. The main centers of glaciation were the peninsula mountain structures. In the middle Pleistocene, widespread development of glaciers is noted, with a thickness of up to ~1000 m. At the same time, manifestations of areal acid volcanism are observed. Acidic magma chambers shielded heat flows of the mantle basalt reservoirs, partially generated and accumulated heat that fed the hydrothermal system of the Pauzhetsky geothermal region and increased the thickness of the granite layer of the Earth's crust. Products of areal acidic volcanism are represented by ignimbrites, pyroclastic deposits, and extrusive lava complexes.

2.2 Ignimbrites

For the first time these rocks were described by Pyip B.I. (1947). He defined them as liparites and dacitic tuffs. At that time, publications about ignimbrites, sintered tuffs and tuffolavas were not yet known. The ignimbrites of the Pauzhetsky geothermal region were studied by Aprelkov (1961). In accordance with their area distribution in the Golygin mountains, they were allocated to the marking Golygin horizon. It was assumed, that they formed on the border of the Pliocene and Pleistocene. Ignimbrites cover with a continuous cloak the rocks of andesite-basaltic volcanoes of the Miocene-Pliocene (Fig. 2).

They are often characterized by columnar separateness. The total area of ignimbrite distribution is about 80 km^2, and the volume is about 10 km^3. The ignimbrites of the eastern part of the Golygin mountains compose a series of layers 5-6 km long, which are inclined in different directions from the center of the site (Leonov, 1989). The maximum thickness of the Golygin ignimbrite horizon is up to 200-300 m. Their small fields are widespread on the western and southern frames of the Pauzhetsky volcano-tectonic depression. According to Kozhemyaka N.N. and others (Long-Living Center ..., 1980), eruptions of ignimbrites came from many small eruptive channels located along faults. In some cases, they erupted from the faults. Emissions to the atmosphere and air transport over long distances were not noted.

Ignimbrites consist of fragments (25-40%), plagioclase crystals (40%), quartz (25-40%), hornblende, pyroxen, biotite, and rock fragments enclosed in a vitrophyric groundmass. The vitrophyric groundmass in the lower parts of the horizon has a distinct fluid texture. In the upper parts, it is not observed. Texture changes are gradual. Sometimes crystal fragments are surrounded by glass. Near microscopic pores and crystals, glass partially crystallized. At the base of the horizon, most of the ignimbrites are monolithic. Lenticular glassy inclusions (fiamme) have a sub-parallel orientation. Lenses reach 5-8 cm in length, the thickness of the lenses is different. The phenocrysts in them are represented by andesine and green hornblende. The groundmass of the fiamme has pearlite texture. The chemical composition of ignimbrites is rhyolite-dacitic and dacitic. The surface of the ignimbrite horizon on the Golygin mountains is almost horizontal.

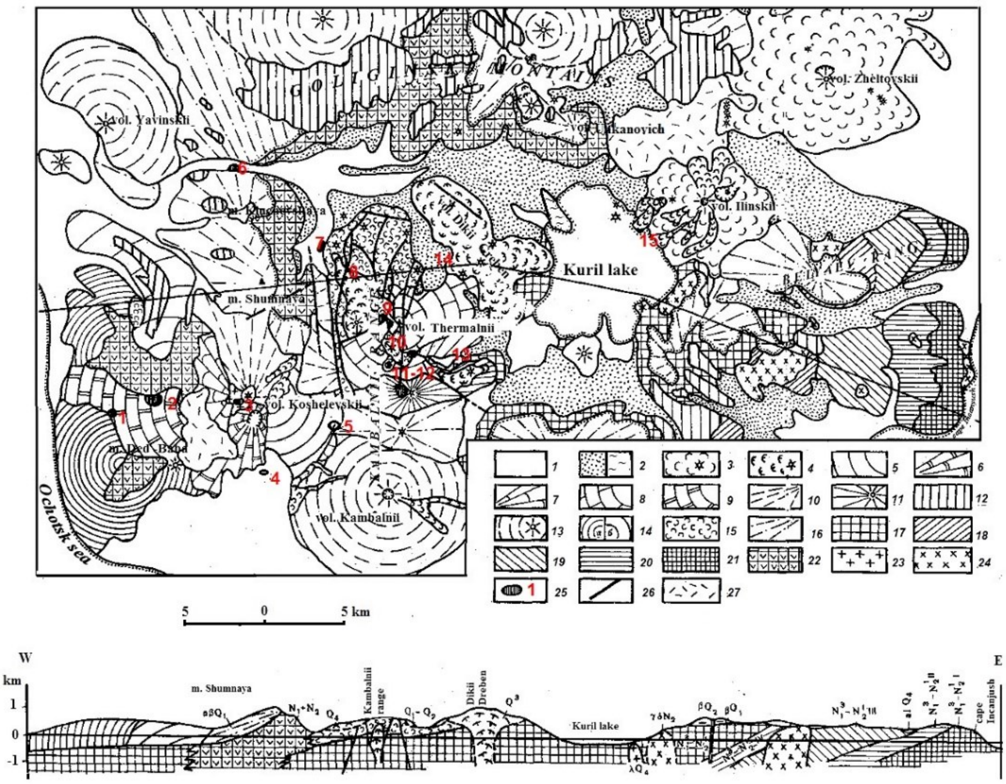

Figure 2: Schematic geological map of the Pauzhetsky geothermal area (Belousov, 1978). 1 - Q_4 - Holocene-alluvial, proluvial and glacial deposits; 2 - Q_4 - Holocene, pumice-caked tuffs of the Pulomynk Peninsula; 3 - Q_4 - Holocene, basalts, andesite-basalts of active volcanoes; 4 - Q_3 - Q_4 - Upper Pleistocene-Holocene, dacite rhyolite extrusive domes and their lava flows; 5 - Q_3 - Q_4 - Upper Pleistocene-Holocene, andesites of the East Koshelevsky volcano; 6 - Q_3 - Q_4 - Upper Pleistocene-Holocene, andesite-basalts of the Central Koshelevsky volcano; 7 - Q_3 - Upper Pleistocene, Valentine volcano andesites; 8 - Q_3 - Upper Pleistocene, andesite-basalts of the Thermalny volcano; 9 - Q_2 - Q_3 - Middle, Upper Pleistocene, andesites of the West Koshelevsky Volcano; 10 - Q_2 - Middle Pleistocene, basalts of the Ancient Koshelevsky volcano; 11 - Q_2 - Middle Pleistocene, andesite-basalts of the Kambalny Range; 12 - Q_2 - Middle Pleistocene, ignimbrites and sintered tuffs of rhyodacite and rhyolite (Golygin horizon); 13 - Q_1 + Q_2 - Lower, Middle Pleistocene, basalts and andesite-basalts; 14 - Q_1 - Lower pleistocene. lava and tuffs of basalt (a) and andesite-basalt (6); 15 - N_2^3 + Q_2 - Upper Pliocene-Middle Pleistocene, dacite tuffs (Pauzhetsky formation); 16 - $N_2$3 + Q1 - Upper Pliocene-Lower Pleistocene. Terrestrial tuff and lava deposits of ancient volcanoes; 17-21 - N_1^3-N_2^1 - Upper Miocene-Lower Pliocene. Marine sedimentary-volcanogenic deposits: V - formation of mainly conglomerates and sandstones, less often tuff-breccia and basaltic lavas; IV - a formation of tuffs and lavas of basalts, tuff-conglomerates; III - formation of tuff-breccia and tuffs; II - a formation of coarse clastic tuffs and basalts lavas; I – a formation of sandstones, conglomerates, less often tuffs; 22 - N_1 + N_2 - unseparated, mainly volcanogenic, sediments; 23 - subvolcanic intrusion of dolerites of the Koshelevsky volcano; 24 - N_2 - Pliocene, subvolcanic intrusions of diorites and diorite porphyrites; 25 - modern thermal fields and hydrothermally alter rocks (*1-Sivuchinsky, 2 – Nizhne-Koshelevsky, 3 - Verkhne-Koshelevsky, 4 - Teplovsky, 5 - Medvezhy, 6 - Ozernovsky, 7 - Pauzhetsky, 8 – Vostochno-Pauzhetsky, 9 -10 – Severo-Kambalny, 11-12 – Juzhno-Kambalny, 13 – Vostochno--Kambalny, 14 - Vitaminy, 15 – Kurilsky)*; 26 — faults; 27 —Pleistocene-Holocene; loose deposits of various genesis.

2.3 Pumice

A late series of acid volcanism eruptions began in the Holocene and is ongoing. In the Pauzhetsky geothermal region, it occurred around the Kuril Lake, on the Ilyinsky and Zheltovsky volcanoes. In the middle and end of the Holocene, a significant part of the southern tip of Kamchatka was covered with pumiceous deposits which were the products of areal eruptions of central type volcanoes as well as scattered eruptive channels. The total area of pumice coverings is ~ 2000 km^2 and the volume is 70-100 km^3 (Long-Living Center ... 1980).

The most intense Holocene phase of pumice formation was manifested near the Kuril Lake. The thicknesses of pumiceous horizons reach 100-110 m and more. The total area of pumice cover formed by streams is 320-350 km^2, and the volume is 22-25 km^3. In addition to the flow, primary pumice deposits are distinguished. Some of them are directly connected with the Ilyinsky and Zheltovsky volcanoes before the formation of the calderas. Several centers of pumice eruptions of high power are distinguished. The Holocene age of the pumice of the Kuril Lake near the volcano Diky Greben, determined by the radiocarbon method, is determined by the interval 8350-8400 ± 200 years (GIN-728, GIN-1060) (Long-living center .. 1980). Small pumice horizons date from the Middle and Late Holocene.

One of the largest centers of acid volcanism of the Pauzhetsky depression is the Diky Greben volcano. It has an andesite-basalt construction with an explosive caldera (3x6 km) which houses a complex extrusion construction. The main volume of pumice is in the valley of the Ozernaya River. They formed a dam with a height of 240 m, as a result of which the level of the Kuril Lake rose (Belousov and Belousova, 1990). Pumice lie on the ignimbrites of the Pulomynk Peninsula. The composition of ignimbrites is dacitic ($SiO2$ ~ 62%).

Pumice flows were "cold". The maximum power of the flows is observed at the exposure of Kutkhiny Bata and decreases very quickly towards the foot of the Golygin mountains (Long-Living Center ..., 1980).

Pumice in the valley of the Ozernaya River has a rhyodacite and rhyolite composition. Pumice stones in the Khakitsin River valley are similar to pumice stones in the Ozernaya River valley. It is assumed that their origin is associated with the formation of an extrusion complex of the Diky Greben volcano. Its area is ~ $120km^2$, and the volume is 10-11 km^3. Pumice consists of several layers, among which there are horizons of ignimbrites and beds of slag the thickness of which increases towards the summit caldera (diameter 4-5 km) of the Ilyinsky volcano.

It is assumed that the Holocene pumices around the Kuril Lake and in the Pauzhetsky volcano-tectonic depression are characterized by complex petrographic and chemical compositions. They lie on pumice gravel deposited in lakes. The pumice stratum consists of several streams of different lengths, thickness and chemical composition, and vary along the strike of the facies. In general, the stratum is characterized by a homogeneous massive texture with rare lenses of coarse pumiceous deposits. The first pumice flows formed simultaneously ~ 8400 ± 200 years ago (early Holocene Q_4^2). Probably, in the middle Holocene, Ilyinsky pumices formed, which alternate with pumices of the Zheltovsky volcano.

Pumice flows are associated with different types of eruptive channels, but most of them erupted from explosive summit craters (calderas) of large stratovolcanoes (Ilyinsky, Zheltovsky). It is assumed that the eruptions partially occurred along the circular faults of these volcanoes that occurred before the eruption. Some eruptions occurred at the foot of stratovolcanoes along faults near extrusions or along faults away from volcanoes and extrusions (Long-Living Center ..., 1980). The main centers of eruptions are associated with the Diky Greben volcano and the calderas of the Zheltovsky and Ilyinsky volcanoes.

2.4 Acidic Volcanic-sedimentary Deposits of the Pauzhetsky Depression

Due to geological exploration, the volcanic-sedimentary complex of acidic rocks in the northern part of the Kambalny Ridge has been sufficiently studied. It is known as the Pauzhetsky Formation. Various rocks participate in its structure, the sedimentary origin of which is beyond doubt (Fig. 3).

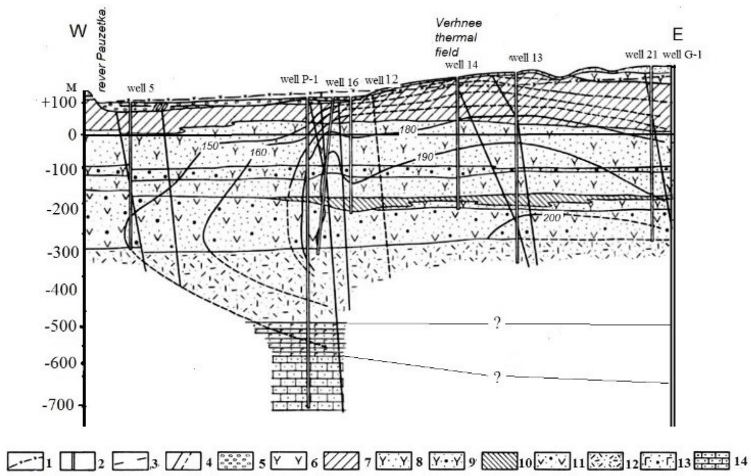

Figure 3: Geological-hydrological section of the Pauzhetsky deposit of thermal waters (see fig. 6). 1 - piezometric level of thermal waters; 2- exploration wells; 3 - geoisoterms; 4 - tectonic faults: discovered and assumed; 5 - alluvium; 6 - lava and lavobrekchii of andesite-dacite; dacite tuffs; 8 – 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 tuff-breccias; 14 - sandstone.

The Pauzhetsky Formation is underlain by the horizon of lithocrystalloclastic tuffs of dacites, at the base of which is a thickness of layers of tuff breccias, andesite lavas and andesite-basaltic lavas. The thickness of the lava flows is 0.5-5.0 m. The space between the fragments is filled with lithocrystalline tuff similar to the tuffs located above. The total thickness of this layer is 80 m.

The lithocrystalloclastic tuff, in appearance, is similar to ignimbrites. These rocks Aprelkov S.E. correlated with the ignimbrites of the Golygin mountains (Golygin horizon). Since these rocks are located at different absolute heights (- ~ 400 m and + 500 m), it was assumed that the Pauzhetsky depression is a graben (Averyev, Svyatlovsky, 1961). The degree of hydrothermal alteration of these tuffs is 3-5% of the rock mass. Under the microscope, the rock consists of 50% crystals and their fragments, consisting of quartz, plagioclase, hornblende, augite and fragments of andesite and andesite-basalt lavas, cemented with colorless transparent glass. Most of the crystal fragments are angular. Numerous fluid inclusions are present in phenocrysts of quartz and plagioclase. Quartz is often corroded and there is a halo of small quartz crystals around it.

Since this horizon lies on sea sandstones and mudstones of the Upper Miocene-Pliocene, it is assumed that the horizon of lithocrystalloclastic tuffs of dacites and the underlying lava-tuff breccia layer dates from the Lower Pleistocene. According to Belousov V.I., these tuffs, formed on the slope of the subaerial volcano Thermal, served as the aquifer of the hydrothermal system of this volcano, in which silica gel deposition and silicification occurred as a result of interaction with sea water (Belousov and Belousova, 2019).

Above the horizon of lithocrystalloclastic tuffs is the Pauzhetsky Formation, which dates from the Middle and Upper Pleistocene. It is composed of volcanic-sedimentary rocks, which were deposited in the Pauzhetsky volcano-tectonic depression. The rocks are mainly represented by pumice and ash tuffs of dacitic, rhyodacitic, and rhyolitic, which in the vicinity of surrounding volcanoes alternate with horizons of tuffo-conglomerates which thickness decreases rapidly as the distance from them increases. It is assumed that the rocks of the Pauzhetsky Formation are products of underwater eruptions of acidic melts.

2.5 Acid Melts Extrusion

The eruption of ignimbrites, pumices and volcanic-sedimentary deposits of the Pauzhetsky Formation often was accompanied by the formation of extrusive domes. Some of them had small flows of considerable thickness. There are rare lava flows of rhyodacite composition the thickness of which can be several meters. Such lavas are observed on the western slope of the Kambalny Ridge near the South-Kambalny thermal field.

There are two types of acidic extrusions. Extrusions of the first type are located in craters or calderas of long-lived volcanic centers (Zheltovsky, Ilyinsky, Unkanovich, Koshelevsky, Thermalny and the Shumny-Klyuchevskaya paleovolcano). Typically, these extrusion domes have or had thermal manifestations with extensive acidic hydrothermal changes. The rocks of these extrusions were andesitic and acidic. Acidic thermal waters heated by steam transformed the host rocks, turning them into opals and argillites. It is assumed that glaciers, snowfields or thick fogs characteristic for island volcanic arcs were involved in the formation of such acidic waters. In the Pauzhetsky geothermal region, this is confirmed by the presence of the moraine of the last valley glacier near the caldera extrusion of the Thermalny volcano.

3. BANNO-PARATUNSKY GEOTHERMAL AREA

The Banno-Paratunsky (Paratunsky - according to Belousov, 1978) geothermal area was identified on the basis of the geological and structural features of the hydrothermal systems included in it, and its location to the folded-block structure of the Nachikinsky graben. Geological exploration was carried out by Belousov (1978), Serezhnikov and Zimin (1976), Sheimovich (1979), Leonov and Rogozin (2007) who generalized a large factual material obtained both as a result of personal research and of another geologists.

3.1 Geology of the Banno-Paratunsky Geothermal Area

The Banno-Paratunsky geothermal region is a mountain range with individual peaks up to 1200-1300 m high. These mountain peaks rising above a plateau-like relief are dissected by V-shaped valleys and eroded by glacial circuses and cars. The region is localized in structural-facies zones, composed mainly of dislocated sedimentary and volcanic-sedimentary formations of the Mesozoic and Paleogene-Neogene age. The Upper Miocene-Pliocene formations comprise the ruins of the stratovolcanoes Shemedogan, Yagodny, Goryachaya Sopka (Goryachy), Karymshinsky and others (Fig. 4).

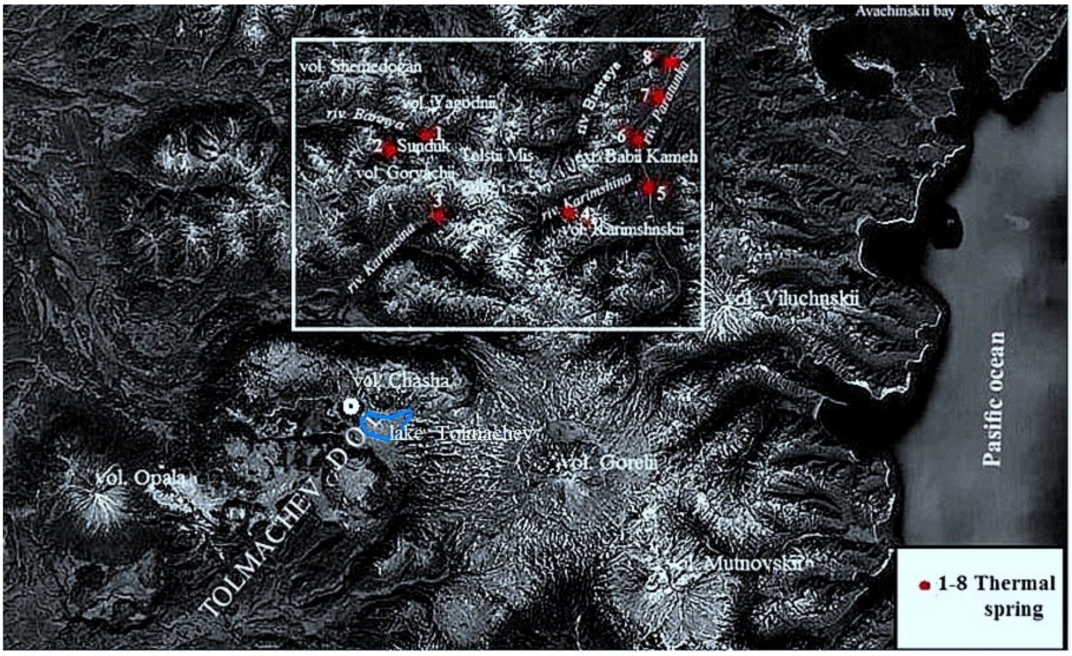

Figure 4: Photo Google. Location of Banno-Paratunsky geothermal region. Thermal sources are shown: 1- Bolshy-Banny; 2 – Malo-Banny; 3-Karymchinsky; 4-Karymshinsky; 5-Verhne-Paratunsky; 6-Sredne-Paratunsky; 7-Nizhne-Paratunsky; 8-Severno-Paratunsky.

The rocks are represented by basalts, andesite-basalts, andesites and their tuffs. Pyroclastic deposits prevail in almost all sections of the series. The accumulation of deposits occurred in subaerial conditions. The maximum thickness is about 500-600 m. According to Leonov and Rogozin (2007), Tolsty Mys Mount is a block elevation composed of tuffs and ignimbrites of the Karymshinsky complex. It is limited by faults of the north-western direction.

Along the boundaries of the uplift, both from the south-west and north-east, there are numerous small volcanoes and extrusions of basalt and andesite-basalt composition. The thickness of the formations composing the geothermal regions of this group is measured in hundreds of meters, often reaching tens of kilometers in some sections (Grib et al., 1976).

In most cases, volcanic-sedimentary formations of Paleogene-Neogene age are altered by high-thermal waters. These processes significantly influenced the filtration properties of the rocks. Acidic and andesitic volcanism is manifested in the form of extrusions and extrusive massifs. They have the forms of regular cones, obelisks, ridges, arrays of irregular shape, domes or rows of domes. The extrusion Sunduk has an obelisk in the form of a table mountain characteristic for Iceland (Fig. 5).

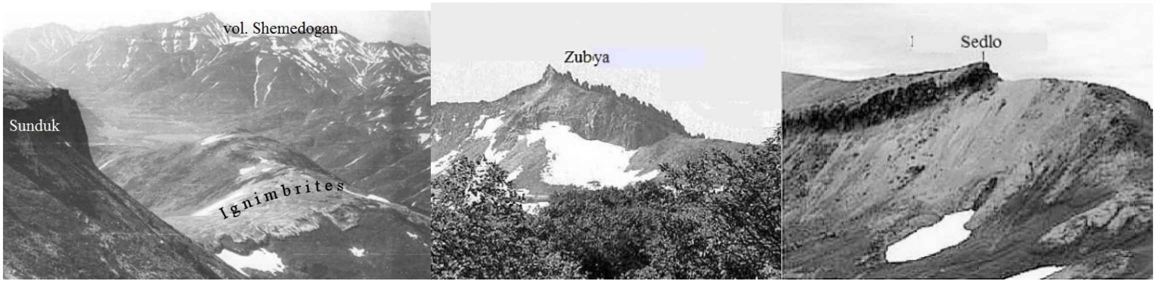

Figure 5: Acidic extrusion on the volcanoes of Banno-Paratunsky geothermal region. Extrusion Sunduk with a flow of ignimbrites. (Sheimovich and Golovin, 2003).

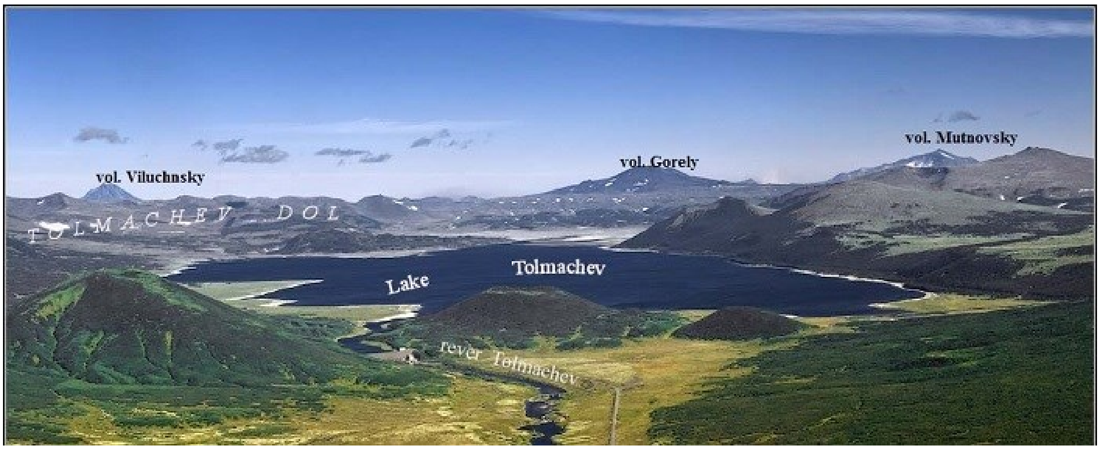

Figure 6: Tolmachev Dol - manifestations of basalt areal volcanism. See location in Fig. 4.

Basaltic volcanism manifests itself in the form of scattered monogenic volcanoes with small lava flows (fig 6). The tectonics of these areas is characterized by intense folded-block dislocations. The individual structures of these zones have large linear dimensions, reaching a width of tens of kilometers and a length of several tens of kilometers. The linearity of geological structures within the zone is emphasized by the corresponding location of sources within geothermal areas.

In the eastern part of the Banno-Paratunsky geothermal area, thermal springs are located along the left side of the Paratunka River valley (Verhne-Paratunsky, Sredne-Paratunsky, Nizhne-Paratunsky, Severno-Paratunsky). (fig. 7).

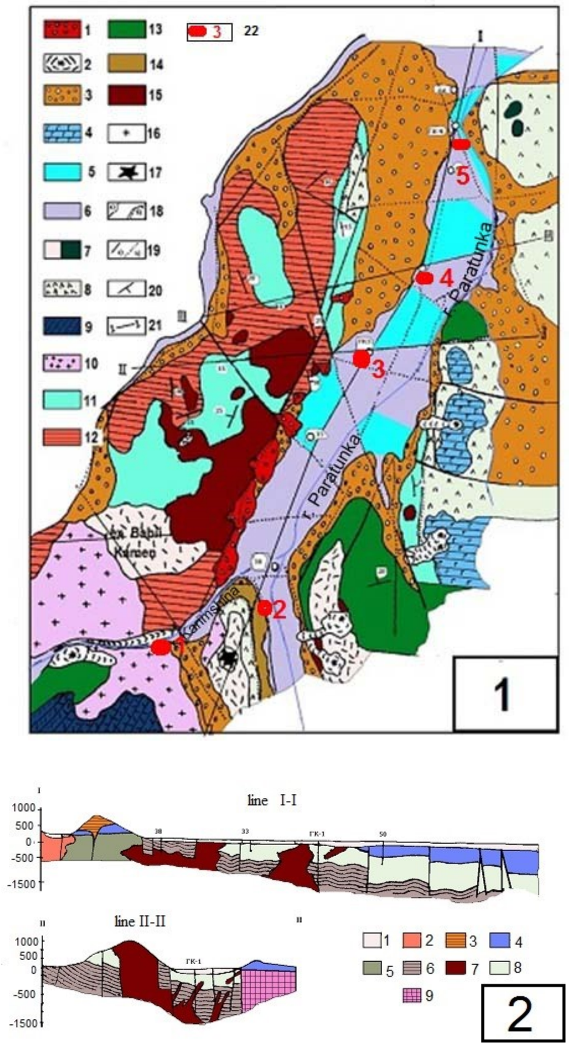

Figure 7: The eastern part of Banno-Paratunsky geothermal area.

1 - Schematic geological map of the Paratunka hydrothermal system: Holocene-Pleistocene: 1 - deposits of modern outflow cones; 2 - slags and lavas of modern olivine basalts; 3 - Upper Pleistocene glacial and water-glacial deposits; 4 - Lower Pleistocene basalts of plateaus and shield volcanoes; 5 - Upper Pleistocene - Holocene alluvial-proluvial deposits; 6 - Lower Pleistocene terrigenous formations of the Paratunsky depression; Miocene - Pliocene: 7 - extrusion of liparites, dacites and andesite-dacites; 8 - lavas of andesite-basalts and basalts; 9 - tuffs and ignimbrites of dacites and liparito-dacites; 10 - subvolcanic array of liparite and laparito-dacite composition; Upper Oligocene - Miocene: 11 - tuffs, tuffites, tuff breccias of andesites, andesite-basalts with subordinate flows of dacitic lavas and small subvolcanic bodies of dacitic and liparitic-dacitic composition; 12 - lavas of olivine and pyroxene basalts, andesite-basalts, their tuffs and tuff breccias; 13 - the thickness is not divided; 14 - tufogenic siltstones, sandstones, agrillites; 15 - Early Miocene intrusions of diorites - diorite porphyrites; 16 - crater funnels of modern basalt buildings; 17 - extrusion of the Sopka Goryachaya; 18 – boundaries of: a) - normal lithological-stratigraphic and intrusive contacts, b) - inconsistent stratigraphic contact; 19 - the main tectonic destruction: a) - in bedrocks; b) - under loose deposits; 20 - elements of occurrence of rocks; 21 - cut lines. 22- Thermal springs (1- Karymshinsky, 2 - Upper Paratunsky; 3- Middle Paratunsky; 4 - Lower Paratunsky; 5 - Northern Paratunsky).

2 - Schematic geological sections of the Paratunsky hydrothermal system: 1 - Upper Pleistocene - Holocene alluvial-proluvial deposits; 2 - subvolcanic massif of rhyolites and rhyodacites; 3 - extrusion of rhyolites, dacites and andesite-dacites; 4 - lavas of andesite-basalts and basalts; 5 - tufogenic siltstones, sandstones, agrillites; 6 - lavas of olivine and pyroxene basalts, andesite-basalts, their tuffs and tuff breccias; 7 - Early Miocene intrusions of diorites - diorite porphyrites; 8 - tuffs, tuffites, tuff breccias of andesites, andesite-basalts with dacite lavas and subvolcanic bodies of dacites and riodacites; 9 - the thickness is not divided.

3.2 Karymshinsky Volcanic Complex

In the Banno-Paratunsky geothermal region, there are welded tuffs and ignimbrites that compose the Karymshinsky volcanic complex (Fig. 8) (Sheimovich, 1979). In some cases, a clear relationship is established between welded tuffs and acidic extrusions and sedimentary rocks. Usually eruptions of pyroclastic flows, from which subsequently welded tuffs form, precede domes crowning extrusion (Fig. 5). The area of extrusive and subvolcanic bodies ranges from 1 km^2 to 20 km^2

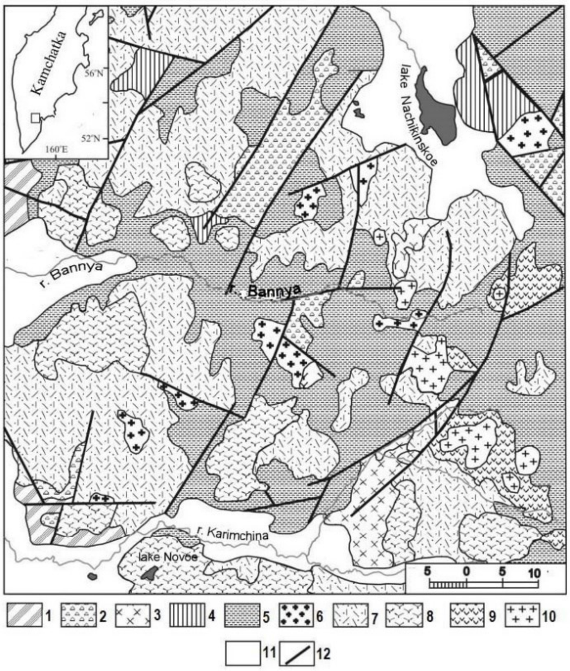

Figure 8: Geological map of the Western part of Banno-Paratunsky geothermal area. The location of the Karymshinsky volcanic complex is shown (Rychagov et al., 2015). Eocene-Lower Miocene: 1 - siliceous volcanic rocks rocks, 2 - terrigenous rocks, 3 - diorite-monzonite intrusions; Middle-Upper Miocene: 4 - tuff sandstone, 5 - rhyodacites - andesites, 6 - a complex of rocks of acidic and andesite composition; Pliocene-Pleistocene: 7 - basalts, 8 - rhyolites, 9 - basalt-andesites 10 - basalts, dacites, ryhodacites and rhyolites; 11 - modern alluvial deposits; 12 - major faults.

According to Sheimovich (1979), in the south-eastern Kamchatka Karymshinsky volcanic complex covers an area of 1000 km2. It is composed of rocks of predominantly acidic composition: ignimbrites, andesite-dacites, dacites and rhyolite tuffs. Their thickness varies within 250–1200 m. The age of the complex is established, as on the basis of faunistic finds (Middle Miocene) in vocanogenic sedimentary rocks. The approximate volume of ignimbrites was determined by different researchers in the range of 300 - 800 km3. Sheimovich (1979) suggested that the thickness of ignimbrites accumulated as a result of eruptions of stratovolcanoes. The cover of the ignimbrites of these volcanoes has significant thicknesses, but do not form large fields.

As a result of previous studies (Sheimovich et al., 1996, 2003), and in subsequent works (Leonov et al., 2010), the determination of the age of the rocks in this complex significantly fluctuates within the Pliocene (1.2 - 1.78 Ma) - late Pleistocene age (0.5 - 0.8 Ma)

This region is characterized by a wide distribution of signs of glaciation of the semi-cover and mountain-valley type of the Middle-Upper Pleistocene and Holocene age. The estimated maximum thickness of the Middle Pleistocene glaciers reached 1000 m. The ancient troughs in southern Kamchatka are cut to a depth of 200-300 m, and these erosion valleys are processed by the younger glaciers which are observed on the stratovolcanoes of the Banno-Paratunsky geothermal region.

Currently, there is great interest in their study in connection with the alleged catastrophic eruptions of the “supervolcano” and the origin of large rhyolites in island arcs (Leonov et al., 2012; Bindeman et al., 2019).

The field of acidic volcanic rocks has the shape of a narrow trapezoid elongated in a north-western direction for 40-45 km. The boundaries of the field are faults that limit the Karymshinsky depression. Its area is ~ 800 km2. The tectonic boundary is well developed in the southeast of the field, where there is no cover of young rocks. Other faults extend along the valleys of the Paratunka and Middle Karymshina rivers. Inside the Karymshinsky depression, faults form a dense network, forming a zone of small blocks of northwestern strike.

The Karymshinsky volcanic complex consists of subvolcanic bodies and covers of tuffs and ignimbrites of rhyolitic and dacitic composition of small thickness. Among the subvolcanic intrusions there are complex bodies of diorite porphyries, quartz monzodiorites and granodiorites. The most widespread are subvolcanic bodies and extrusions of rhyolites and dacites, which are equal or exceed the covers of the volcanic complex in the area of outcrops. Rhyodacite bodies often have a fragmental texture which does not differ from the structure of ignimbrites.

Dacites, rhyodacites and rhyolites have a porphyritic, ignimbrite-like, porphyry-clastic structure, fluid, taxitic texture. They are characterized by numerous xenoliths and homeogenic inclusions. The major part is vitrophyric. The Banno-Karymshinsky depression is distinguished by a negative magnetic field and a gravitational minimum. This section is characterized by the absence of correlated seismic boundaries on seismograms.

The subvolcanic bodies of the Karymshinsky volcanic complex break through volcanic-sedimentary deposits and subvolcanic massifs of the Miocene andesite formation. It is assumed that in the Pliocene-Eocene andesite-basaltic stratovolcanoes were located near acid volcanism zones and that the history of the formation of the Karymshinsky volcanic complex was long - from the end of the Neogene to the Eopleistocene.

3.3 Hydrogeothermal Conditions

Thermal springs in the valleys of the Paratunka and Karymshina Rivers (Karymshinsky, Verkhne-Paratunsky, Sredne-Paratunsky, Nizhne-Paratunsky and North-Paratunsky) are the discharge center of the Paratunsky hydrothermal system. The system is located in the Paratunsky graben, east of the Karymshinsky volcanic complex which is the region of its water supply (see Fig. 6).

The main water-containing complex of thermal waters in the Paratunsky hydrothermal system are Paleogene-Neogene rocks with a dense network of cracks of various genesis which are characterized by high permeability coefficients. Temperatures decrease from south to north, which is consistent with the geological structure. It is assumed that the heat source is located near the Karymshinsky Pliocene volcano, where the Middle Pleistocene extrusion of Babi Kamen and the Upper Pleistocene extrusion are located (Fig. 6).

Bolshaya Bannaya hydrothermal system is located in the same structural and facies zone as the Paratunsky hydrothermal system. The thermal manifestations of this hydrothermal system are concentrated on the periphery of the stratovolcano Goryachiy eroded by glaciers. The Karymchinsky and Maly Banny thermal manifestations, located in the valleys of the Karymchina and Maly Klyuchik rivers, are represented by warm springs with low flow rate and temperatures up to 70°C. However, on the thermal site of the Bannaya River there are "boiling" sources. They are characterized by weak vaporization and small flow rates with a temperature of less than 100°C. Pilot tests of steam-water wells drilled at this thermal site showed a heat content of ~ 170 kcal / kg (Kraevoy et al, 1976). It is assumed that the release of free carbon dioxide in wells and springs occurs at a depth of 2.2 km. It is estimated that at this depth the temperature can be ~ 170ºC.

4. DISCUSSION

A remarkable feature of the products of acid volcanism in the Pauzhetsky and Banno-Paratunsky geothermal regions located in volcano-tectonic depressions is their spatial connection with basaltic and andesite-basaltic long-lived volcanic centers (stratovolcanoes) (Belousov et al. 2020b). Since the eruptions of ignimbrites in these regions occurred along the numerous eruptive vents and were over a large area, we haven't found their connection with supervolcanoes and giant calderas.

In addition, eruptions of both melts and ignimbrites occurring in the Middle Pleistocene with the formation of extrusions (Fig. 5) were characterized by slow extrusion of these masses and the absence of detonation explosions or the eruption of two-phase liquids. This indicates a low internal energy of acid volcanism products. This did not contribute to their extraction from of the Earth's crust, where they were generated. Eruptions of this type are very likely a consequence of external processes, in particular, the pressure of surrounding rocks or glaciers. Confirmation of this conclusion is the simultaneous introduction of extrusions, the formation of the Tolsty Mys Mountain in the presence of powerful glaciers in the Middle Pleistocene.

In the Banno-Paratunsky geothermal region, Leonov and Rogozin (2007) carried out work to refine the geological and structural positions of Bolshe-Banny thermal springs. They believe that there was a giant caldera in the area that experienced resurgence. The boundaries of this structure are not identified reliably because of its large size and the absence of morphological characters.

The hypothesis about the origin of rhyolite rocks of the Banno-Paratunsky region was mentioned above. It is based on the idea of the connection of those rocks with the formation of the caldera in the process of evolution of a supervolcano. The presence of the caldera is not confirmed by the positive magnetic and gravitational anomalies of the corresponding basaltic magma reservoir in the Earth's crust. According to Bindeman and others (2019), additional studies are needed to clarify the nature of the relationship between caldera formation and giant explosions of a supervolcano.

Bindeman and others (2019) presented a model for the formation of the Karymshinsky volcanic complex. It is assumed in it that the formation of bulk magma rhyolites (70–74 wt.% SiO_2) and especially rhyolites with a high silica content (> 74 wt.% SiO_2) can occur as a result of the assimilation and melting of hydrothermally altered rocks rich in silica. In this regard, it seems interesting to study water-containing and water-resistant complexes of modern hydrothermal systems in the fields of modern volcanism.

The Pauzhetsky geothermal region is composed by volcanic-sedimentary formations of the Pliocene-Quaternary predominantly younger than the Banno-Paratunsky geothermal region. It is characterized by increased modern hydrothermal activity, hydrothermal metamorphism and exploration study with the drilling of a large number of geothermal wells. At the Pauzhetsky hydrothermal field, the horizon of lithocrystalline tuffs of dacites, which were previously compared with the ignimbrites of the hydrothermal systems of New Zealand, is now defined as the product of hydrothermal changes. The petrographic characteristics of these rocks are more accurate (Pauzhetsky hot waters, 1965), since the entire section of this horizon was studied with full core sampling of the entire flow of high-temperature water from the Pauzhetsky field (Fig. 3), as well as in the natural outcrops of the Kambalny Ridge.

The horizon of lithovitroclastic tuffs of dacites is located between the volcanic sandstones and argillites of the Miocene and water hyaloclastic tuffs of rhyolite-dacite of the Pliocene-Pleistocene age. These formations fill the Pauzhetsky depression which is surrounded to multichannel volcanoes of the central type. In our opinion, the early stage of evolution of the Banno-Paratunsky geothermal region is consistent with the current stage of development of the Pauzhetsky geothermal region.

Hydrothermal changes in the rocks of the water-bearing complex and water-resistant horizons, which led to the formation of lithocrystalloclastic tuffs of dacites, were manifested in silicification (Belousov and Belousova, 2019) and the formation of hydrothermal minerals with fluid inclusions. It is assumed that the destruction of some of them is caused by the explosion of these fluid inclusions when heated to temperatures above the temperature of their formation (~ 300ºC). In this regard, it is possible that in some places located near the eruptive channels of deep magmatic melts (possibly mantle origin), observed in the vicinity of extrusive manifestations, melting occurs. Since the rocks composing the extrusion contain high concentrations of alkali metals, heat was probably transferred by the thermal diffusion of K and Na, due to the thermal gradient between the deep melts and host rocks (Belousov and Belousova, 2016, 2019).

During the Middle Pleistocene glaciation, plastic acidic melts, influenced by the pressure of glaciers and host rocks, rose and squeezed out welded host rocks heated to a plastic state. This process was supplemented by the influx of deep magma of monogenic injections, which are characteristic for the eruptions of Icelandic volcanoes after the disappearance of glaciers on them (Slater et al., 1998). Faults and cracks around such uplifts served as channels through which boiling and degassing underlying ore-bearing carbon dioxide fluids rose. As a result of this process, quartz-carbonate ore veins were formed (Rogozin, 2009). Catastrophic eruptions did not occur. Significant migration did not occur. Therefore, we proposed to call such ignimbrites *in situ*.

The result of the above discussion, in our opinion, may be the conclusion about the need for an alternative logically consistent hypothesis of the origin of the ignimbrites of both generations in the Banno-Paratunsky geothermal region, based on the evolution of its hydrothermal-magmatic systems of the stratovolcanoes of the island arc.

5. THE MODEL OF GENERATION OF ACID MAGMES OF LARGE VOLUMES IN THE GEOTHERMAL AREAS OF KAMCHATKA

A generalization of the geological history of long-lived volcanic centers development in the geothermal regions of Kamchatka allows us to consider a conceptual system of the interrelations of processes occurring over a long history of formation, activity and death of such a structure.

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

In the Pliocene and Middle-Upper Miocene, on the site of long-lived volcanic centers of Kamchatka geothermal regions, which were located in the fields of areal volcanism, volcanoes were formed with magmatic chambers in the Earth's crust. An accumulation of thermal energy and partial melting of the host rocks occur in these places. If such host rocks contain sulfides or carbon compounds, then additional heat is generated as a result of the redox reactions. This process determines the long-term activity of long-lived volcanic centers (Belousov and Belousova, 2018; Belousov et al, 2020b). The activity of long-lived volcanic centers, in the structure of which crustal magma chambers were located, was accompanied by volcano-tectonic processes. As a result, a closed depression arose between stratovolcanoes and an artesian hydrothermal basin was formed with a limited runoff of thermal waters containing silica gel (Belousov and Belousova, 2019).

The artesian thermal basin is fed by streams of high-temperature waters of hydrothermal-magmatic systems surrounding long-lived volcanic centers (stratovolcanoes). The streams of high-temperature water saturated with silicic acid interact with sea water in an island arc, as a result of which chalcedony and amorphous silica are deposited in water-containing complexes (mineral gas-hydro-geothermal barrier) (Fig. 9) (Belousov and Belousova, 2019).

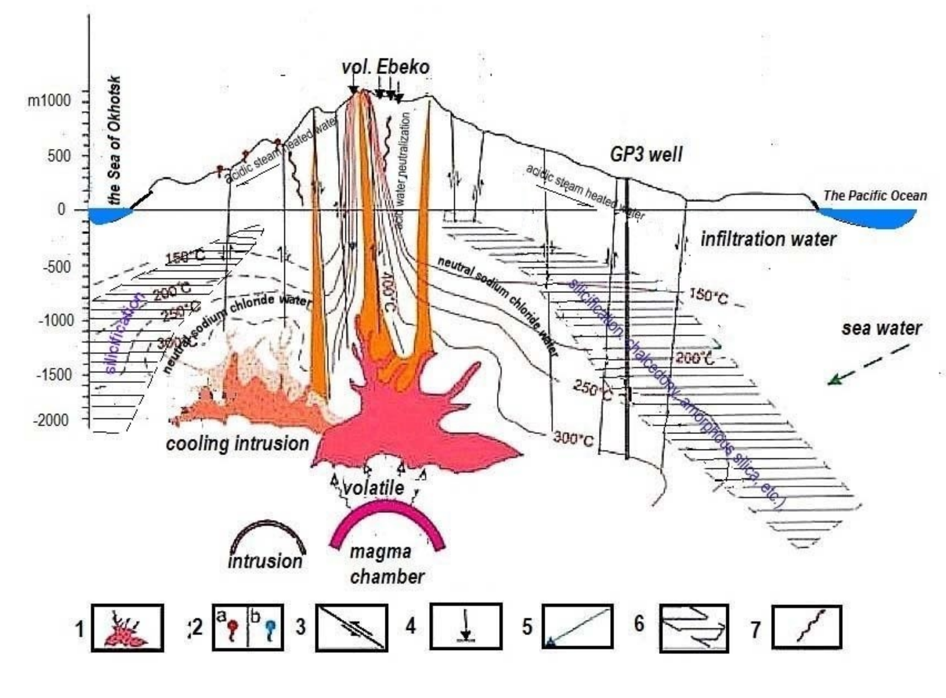

Figure 9: Scheme of the Deep Structure of the Hydrothermal-Magmatic System of Ebeko Volcano. 1. Magmatic Chanel, 2. Thermal Sourses A) Hot B) Cold, 3. Fault Zone, 4. Fumarols, 5. Infiltration Waters, 6. Mineral Gas-Hydro-Geothermal Barrier (silicification: chalcedony, amorphous silica, etc.), 8. Upflow.

This horizon of impermeable rocks (cap rock) has the properties of heat insulators. This process was accompanied by the accumulation of heat with increasing temperature and carbon dioxide, which led to the formation of steam at a depth of ~2 km. The boiling and heat losses in the upper part of the water-containing complex create conditions for the formation of a stratum of high-silicon rocks. Under the conditions of the Middle Pleistocene glaciation, powerful glaciers limit the underground runoff of meteoric waters and, having the properties of a heat insulator, contribute to an increase in the temperature of siliceous rock horizons, which leads to a partial melting of high-siliceous material. Sintering of the rock particles of the water-bearing complex and water-resistant horizons occurs until the plastic mass is formed. If higher-temperature conditions are created, gas and water vapor can be released which leads to the gas-vapor explosions in a type of two-phase flowing jets. In those cases where there is an accumulation of gases capable of exploding (H_2, CH_4 etc.), such eruptions are complicated by detonation explosions (Rychagov et al., 2008).

The thermal waters of the Bolshe-Bannaya hydrothermal system are characterized by a high content of carbon dioxide. It affects their dynamics and chemical-metamorphic processes. The rocks in 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 rocks in the upper part of the stratum near the volcanic andesite-basaltic structure of the Mount Goryachaya is due to the boiling of medium and low temperature thermal waters of the Bolshe-Bannaya hydrothermal system. The boiling depth (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, large heat loss and precipitation of dissolved silica occur. At higher temperatures at great depths, the process of silicification is more intense.

Heat discharge was the result of underground boiling of high-temperature water simulated by degassing, mainly CO_2. Deposition of minerals, formation of horizons of siliceous rocks and thickening of cap rock occurred. During the Middle Pleistocene glaciation a similar role in this process was played by glaciers (Belousov and Belousova, 2018). High CO_2 concentrations formed carbonic hydrothermal solutions with high Ca-silica gel contents. It adsorbed metals and transformed into an ore-bearing fluid (Belousov and Belousova, 2019).

Plastic acidic melts, influenced by the pressure of glaciers and host rocks, were squeezed up and deformed the horizons of ignimbrites and host rocks. It is assumed that this process was stimulated by injections of mantle melts of areal volcanism, enhanced by the degassing of the accumulated phase of volatile components.

Faults and cracks around such uplifts served as channels through which boiling and degassing underlying ore-bearing carbon dioxide fluids rose. As a result of this process, quartz-carbonate ore veins were formed (Rogozin, 2009). Catastrophic eruptions did not occur. Significant migration did not occur. Therefore, we proposed to call such ignimbrites *in situ*.

6. CONCLUSION

Although the hypothesis about the origin of the vast masses of acid volcanism products associated with the formation of calderas, which is based on the idea of crystallization differentiation, is undergoing reasonable doubts, it remains the main concept in geology. However, over many years of research, the problems of bimodal volcanism have not been solved by the concept of crystallization differentiation (Berg, 2016).

Bindeman and others (2019) took several steps with the proposal to search for a new idea. They presented the data of their researches on the basis of which it is assumed that the formation of bulk magma rhyolites (70-74 wt.% SiO2) and especially rhyolites with a high content of silica (> 74 wt.% SiO2) can occur as a result of assimilation and melting of hydrothermally altered rocks rich in silica.

In our opinion, the hypothesis proposed here has both fundamental general geological significance in solving the problem of bimodal magmatism and practical interest in the study of ore formation processes and the energy use of geothermal heat. The studies are being undertaken in this direction on the basis of “megagrant No. 14.W03.31.0033 of the Ministry of Education and Science of Russia “Geophysical research, monitoring and forecasting the development of catastrophic geodynamic processes”. This work has been carried out in the framework of the Russian Far East.

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