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The evolution of the magma chamber of the Kikhpinych hydrothermal-magmatic system. Kamchatka

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ABSTRACT

The Valley of Geysers on Kamchatka Peninsula is the part of the Kikhpinych magma-hydrothermal system. The crust magma chamber is a source of heat supply for the Geyser hydrothermal system. Its growth in the Quaternary period coincided with the presence of the glacier cover. It is assumed that the glacier limited the infiltration of water into the subsurface magma-hydrothermal system and at the same time played the role of a heat insulator. Beneath it, the heat transported by the volcano Kikhpinych accumulated, and a thermal field was formed sufficient for partial melting of rocks altered by hydrothermal processes.

The intrusion of high-temperature mantle melts was accompanied by the formation of mixed melts. They contained mantle gases (CO_2 and H_2). Subsequent injection of mantle melts led to the strong steam-gas and detonation explosions which formed ignimbrites. They could spread along the glaciers surface over long distances.

Evacuation of large volumes of materials in the magma chamber area stimulated the inflow of high-temperature mantle melts into the magma chamber and the increase in the flow of trans-magmatic heat-transfer agents (alkali metals). The high temperature in the melting zone resulted in the formation of high-temperature silicic melts released from the Earth’s crust as an effusive eruption.

The disappearance of glaciers and permafrost during the interglacial period and the formation of effusive structures were accompanied by an increase in the downward flow of meteoric waters. They cooled the magma chamber in the Earth's crust, and that resulted in the reduction of the crustal magma chamber towards the volcano Kikhpinych.

1.0. INTRODUCTION

Central volcanoes are formed as a result of repeated eruptions from the central eruptive system which is supported by long-life streaming system (Gudmundsson, 1995). Most of these systems are fed from the magma (peripheral) chambers located superficially in the Earth's crust. These chambers are a trap for ascending flows of the mantle (basaltic) magma.

Volcanoes with peripheral chambers characterize by excessive degassing of SO_2 (Shinohara, 2008). It is assumed that excessive degassing of SO_2 and CO_2 at these volcanoes is due to the exothermic oxidation-reduction reactions (combustion). Melting of the host rocks and dynamic degassing manifested in the form of ignimbritic eruptions, form the space of the peripheral chambers. The Kikhpinych magmatic-hydrothermal system formed a long-life volcanic center which is a typical central volcano (Belousov, 1978). Formation and evolution of the magma chamber in the crust of the volcano Kikhpinych play an important role in its activities and shaping the flow of thermal waters which is discharged in the valley of the Geyzernaya River (Belousov et al, 1984).

2.0. KIKHPINYCH LONG-LIFE VOLCANIC CENTER: STRUCTURAL POSITION, ROCKS, CRUST MAGMATIC CENTRE

The Kikhpinych long-life volcanic center is located in the north-eastern sector of the Semyachik geothermal area in the upper Geyzernaya River. The central volcanic structures of the Semyachik area are controlled by the intersection of the Eastern-Kamchatka deep-seated tectono-magmatic fault and transverse faults (figure 1).

This volcanic center has elliptical shape (Fig. 2). The direction of the long axis coincides with the overall direction of tectonic faults and the location of extrusions developed to the south-west from the Kikhpinych volcanic center where the thermal manifestations in the Valley of Geysers are located. The Kikhpinych long-life volcanic centre was formed within the tectono-magmatic rift, and the individual elements of its structure are subordinated to the structure of the deep fault. In the formation of the Kikhpinych long-life volcanic center, there is a monogenetic volcano. In its south-eastern part, together with the eruptions of the basalt lavas, an extrusive dome was formed (Zheltaya mountain) near which is a large field of rocks altered by acidic thermal waters.

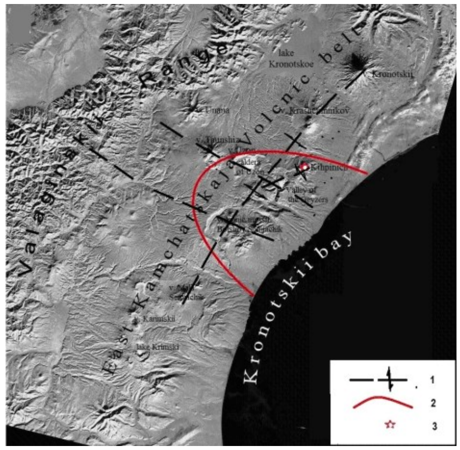

Figure 1: Photo of the Eastern-Kamchatka volcanic belt. 1 – Eastern-Kamchatka deep-seated tectono-magmatic rift; 2 - border of the Semyachik geothermal area; 3 – the Kikhpinych long-life volcanic center.

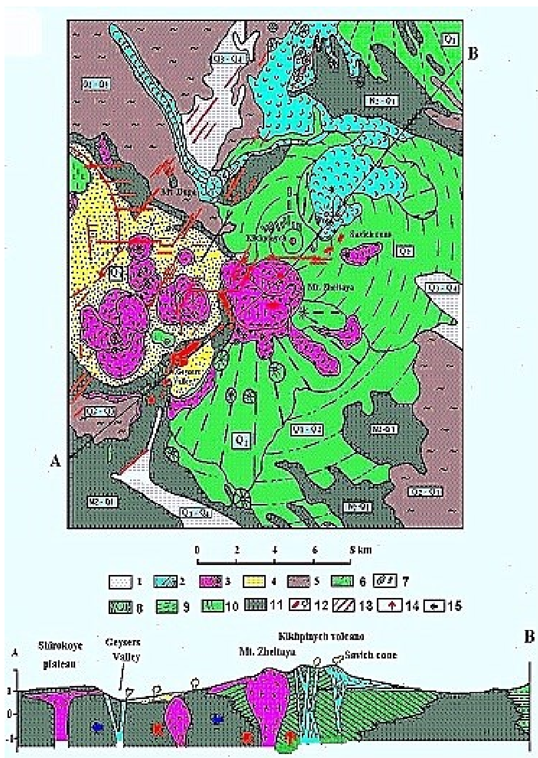

Figure 2: Geologic map of the Kikhpinych long-life volcanic center and hot Spring hydrothermal system. 1 - Upper Pleistocene - Holocene. Alluvial, proluvium and glacial sediments. 2 - Holocene, basalt, andesite. 3 - Middle Pleistocene. Dacite, rhyolite. 4 - Upper Pleistocene. Lacustrine deposits. 5 - Upper - Middle Pleistocene. Ignimbrites. 6 - Upper Pleistocene. Basalt. 7 - Middle Pleistocene. Dykes and monogenic volcano. Basalt. 8 - Middle Pleistocene. Kikhpinych volcano. Basalt. 9 - Middle Pleistocene. Gorelyi plateau. Basalt. 10 - Low-Middle Pleistocene. Basalt, andesite. 11 - Pliocene - lower Pleistocene Complex. Tuff, lava of basalt and dacite. 12 - Hydrothermal fields and hydrothermally altered rocks. 13 - Fault zone. 14 - Endogenic mass and heat flow. 15 - Regional flow of groundwater.

On the right bank of the Geysernaya and Shunaya rivers, the extrusions Geysernaya, Krugloye plateau and Shirokoe plateau are located, having the form of table mountains (Fig. 3). Between the Geysernaya extrusion and Krugloye plateau is the extrusion Ostanez with the lava flow in a glacial trough. The eruption of extrusions began with the formation of pumiceous deposits poured by rhyolite, rhyodacite, and dacite flows. Rocks of extrusions unaltered acidic thermal waters.

Geological structure of the Kikhpinych long-life volcanic center differs from the geological structure of the deep tectono-magmatic fault in more concentrated location of eruptive centers per unit of area. Eruptive centers of the holocene age are located along the long axis of the ellipse of Kikhpinych long-life volcanic center. Dikes of basalts near the apical part of the Old Kikhpinych are fan-shaped. The volume of the erupted material from this channel exceeds the rocks volume from eruptive centers of the deep tectono-magmatic fault. In the early stages, it was a volcano of the central type. During this period the Kikhpinych stratovolcano was composed of the archipelago of Islands and its eruptions have occurred in air conditions. Around these volcanic structures in the neogene siliciclastic sediments were deposited, which are composed of volcanogenic-siliceous rocks. The thickness of these sediments is ~7 km.

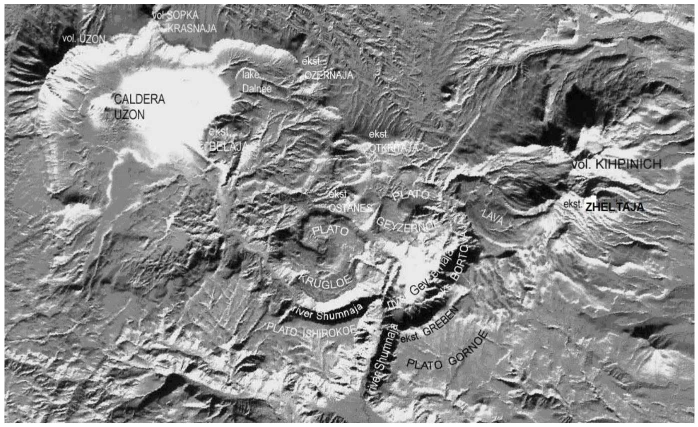

Figure 3: Photos from the Space. Shown: the Uzon caldera, the Kikhpinych volcano, canyons of Shumnaya and Geyzernaya rivers, plateau-extrusions.

In the Pleistocene and Holocene the stratovolcano Kikhpinych was characterized by the decentralization of eruptive activity. Acidic magma erupted into the upper horizons of the Earth's crust in a large area (areal acidic volcanism). In the canyons of Geysernaya and Shumnaya rivers dikes of rhyodacites are observed in the volcanogenic-sedimentary strata of the same composition. It is assumed that these layered basalt deposits were formed in the subglacial lakes of calder depressions which were formed as the result of the eruptions of large pyroclastic flows (ignimbrites). Significant areas of altered rocks near the dikes are the evidence of their long-term cooling. It is assumed that a significant amount of heat received by the dyke by trans-magma fluids.

Like lava flows and pyroclastic strata of the sediments of the Old Kikhpinych, Volcano Zheltaya (extrusive dome) on the Kikhpinych volcano changed by acidic (pH = 3-4) and ultra acidic (pH<2) hydrothermal fluids, almost throughout all history of the center.

We have not yet determined the direct link of basaltic dikes in the southern part of the Kikhpinych long-life volcanic center and extrusions of rhyolites and dacites belonging to the structure of the Geyzernaya hydrothermal system. However, a number of circumstantial evidences suggests such a connection (Belousov et al, 1984). The study of extrusions associated with Geyzernaya hydrothermal system confirmed a great depth of the generation of some plagioclase phenocrysts. The presence of gas bubbles in them allows determining the composition of gas inclusions and the pressure at which they were formed. They consist of nitrogen and are under a pressure of about 8 kbar which corresponds to the generation depth about 30 km. These data show that in the depths of the Kikhpinych long-life volcanic center the magmatic centre is located at a small depth, and it interacts with the zone of basaltic melts generation in the upper mantle. The findings in the area of Pliocene age acid rocks suggest that this source existed in the subsurface area of the Pliocene. His activity was interrupted by periods of rest, when there was a partial crystallization of the hearth.

Three cycles of eruptions exist. At the beginning of the first cycle (middle Pleistocene), basaltic magma with a temperature of 1340—1300°C intruded in the chamber with the acidic magma which had a temperature close to the solidus. The introduction of basaltic magma was accompanied by a partial melting around the channels of rocks, whose composition was close to that of granites. At this time the andesite lava poured out upon the surface. The last lava flows were more acidic. The granite melt mixed with the basaltic magma, and the thermal energy was spent on phase transitions. The hearth reached the highest degree of heat at the end of the first cycle, as evidenced by a small amount of phenocrysts (3-6%) in rhyolites of that time. At that time the melt contained a small amount of water. The upper bound of the hearth was at a depth of 7-8 km and its diameter was about 10 km.

In the second cycle (early upper Pleistocene) there was a powerful eruption of rhyolites. The temperature of molten inclusions in the recent lava flow of Krugloye plateau (1090-1060°C) showed that the temperature of the melt before the eruption was not less than ~1000° C. After the second cycle of activity the accumulation of volatile components in the hearth took place. The third cycle was characterized by the introduction of high-temperature basaltic magma in the area of Geyzernaya extrusion along the latitudinal system discharges. Volatile components are H_2, CO_2 and hydrocarbons.

The decline in products of acidic volcanism from cycle to cycle and increase in the degree of lavas crystallinity show a gradual crystallization of the chambers. However, in the Holocene it became active due to the introduction of a primary magma similar to the magma of the young cinder cones. Thermal pulse into the upper, partially crystalline part of magma melted it. Thus, in the present time, the magmatic chamber in close proximity to the edifice of the Kikhpinych long-life center probably has a temperature above the solidus of the granite system.

The geological structure of the Uzon-Geysernaya area, magmatism and hydrothermal activity are characterized by the trend of rejuvenation from east to west. The Geyzernaya hydrothermal system dates back to the beginning of the early Middle Pleistocene (250-300 thousand years), and the hydrothermal system of the Uzon Caldera - to the beginning of the Late Pleistocene (100-150 thousand years).

Surface discharge of hydrothermal systems comes from the lacustrine deposits of the Uzon-Geysernaya erosion-volcanic depression. Those deposits also have different ages in the eastern and western parts.

Although thermal manifestations in the Valley of Geysers and Uzon Caldera are disconnected by the field of acid volcanism manifestations, it is assumed that at shallow depth they have a uniform source of heat supply which is the magma chamber (system of magma chambers). In addition, it is an accumulator of mantle heat. It is also believed that these systems are united at the depth by a common aquifer (Fig. 4).

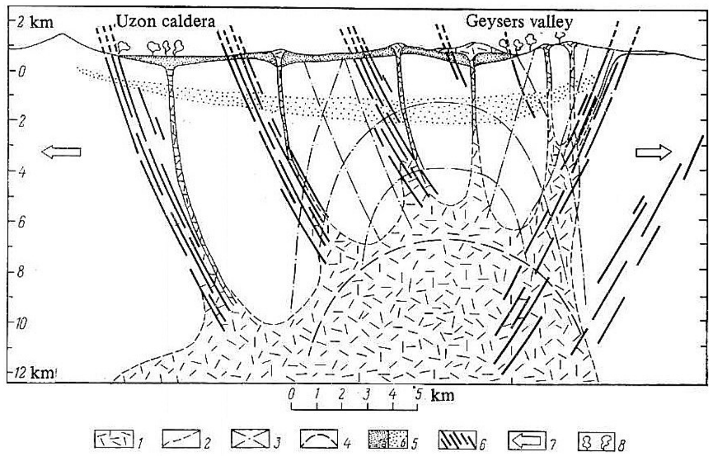

Figure 4: The conceptual model of the Kikhpinich hydrothermal-magmatic system (Belousov et al., 1984). 1 — development of a magma chamber (system) in the Earth's crust; 2— hypothesized borders of the magma chamber; 3 — the system of ring and cone cracks and dikes above the chamber; 4 – an idealized upper limit of the chamber in the period of introduction of the dikes (Q_2); 5 — aquifer complexes: a — upper, b — lower; 6 — fracture zones; 7 — direction of the extension of the crust in the area; 8— manifestations of hydrothermal activity.

According to the simulation results, the most possible source of deformation is the sloping sill of irregular shape in the depth range of 4-8 km beneath the eastern part of the Uzon-Geysernaya depression, the linear dimensions of which are roughly 9×15 km (Kugaenko and others, 2016).

In the course of the seismological field survey in 2008-2009 a large number of weak local earthquakes with KS=3-7 was registered. The epicenters of the earthquakes are located compactly and mostly fall under the Kikhpinich long-life volcanic center (Fig. 5). The depth of earthquakes does not exceed 5 km. The deepest earthquakes are located under the extrusions in the eastern part of the Uzon-Geysernaya depression. A large part of the seismic events is associated with the area of hydrothermal manifestations in the western part of the Kikhpinych volcanic massif.

Events gr. G are not numerous. They fall in the depth range of 1-5 km, plunging from the Valley of Geysers to the West, under the area of extrusive domes in the eastern part of the depression. Earthquakes gr. K occur in the field of the modern hydrothermal manifestations.

Geophysical data, as previously mentioned geological and petrological data, suggest that the geodynamic activization of the Kikhpinych long-life volcanic center is associated with a hidden movement of magma to the surface. It is assumed that the magma intrusion can occur inclinedly, along the periphery of the crystallized magmatic chamber at a depth of 4-6 km beneath the eastern part of the Uzon-Geysernaya depression. Magma comes from the peripheral part of the Kikhpinych volcano or from the deeper magmatic reservoir (Kugaenko and others, 2016).

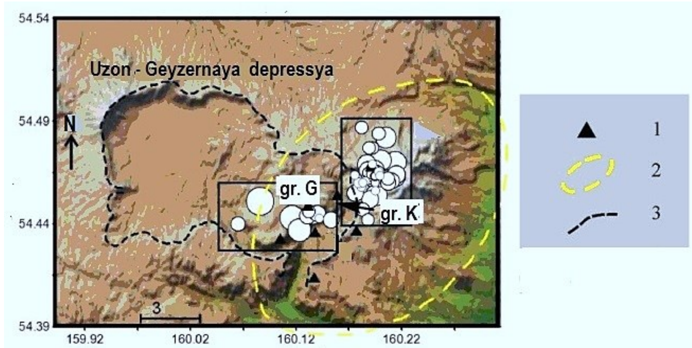

Figure 5: Local seismicity according to the field survey, 2008-2009. It shows the epicenters of earthquakes. : 1 – temporary seismic stations; 2 – the border of the Kikhpinych long-life volcanic center; 3 – the border of the Uzon-Geysernaya volcano-tectonics depression. The Kikhpinych long-life volcanic center is contoured by an ellipse. Described in the textm the group of earthquakes gr. G and gr. K are indicated by rectangles (Kugaenko and others, 1915).

3.0. UPPER QUATERNARY GLACIOVOLCANISM

Erlich E. N. and others (1979) showed that the manifestations of acidic volcanism in the Uzon-Geysernaya depression in the form of ignimbrites, pumice and extrusive domes occurred in the time of Middle and Upper Pleistocene glaciation. Thus, the Kikhpinych hydrothermal-magmatic system was formed under the influence of glacial volcanism (glaciovolcanism).

In recent years, the study of the processes of glaciovolcanism in Iceland opens up the possibility to use the principle of actualism also in Semyachik geothermal area (Licciardi et al., 2007). There are huge covers of ignimbrites on the slopes of the Uzon-Geysernaya erosion-explosive depression, in which formation the volcanoes Uzon and Kikhpinych are involved (Fig. 6).

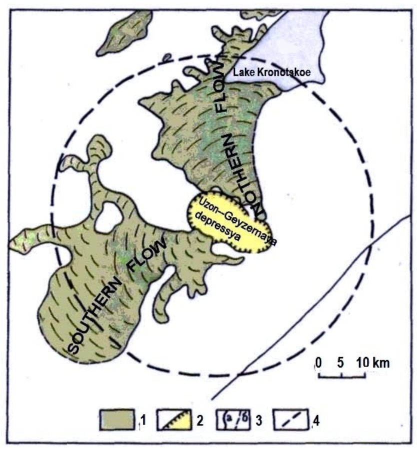

Figure 6: The fields of distribution of the ignimbrites associated with the Uzon-Geysernaya volcano-tectonic depression: 1 - erosional boundary of the depression; 2 – borders of the ignimbrites field; a - determined, б- assumed; 3 – center-lines of the distribution of pyroclastic flows (Grib and Leonov, 1993).

The volumes of these pyroclastic flows are of the tens of km^3. Such eruptions were accompanied by the formation of calderas of different types. Leonov V. L. and Grib E.N. (1999) define the Uzon-Geysernaya depression origins as erosion-explosive. The position and shape of ignimbrites covers indicate that the eruptive centers of the pyroclastic flows which formed these covers were in the eastern part of the Uzon-Geysernaya depression. The study of the coastal sections of such covers in Bolshoi Semyachik volcanic massif showed that the depositions of glaciers intercalated with pyroclastic flows (Chaimowicz, 1979).

Other topographic structures characteristic for this region are table mountains (plateau-extrusion) having a shape similar to tuyas in Iceland (Russell et al., 2014). Magmatic channels, along which the introduction of the acidic melts, occurred, as well as the eruptive centers of the pyroclastic ignimbrites flows, are located in the eastern part of the Uzon-Geysernaya depression. It is assumed that the eruption occurred along straight and ring dykes. They were formed in the presence of glaciers. Their thickness reached several hundred meters. Volcanic edifices have a flat top and steep slopes formed as a result of presence of a barrier (currently non-existent). Probably it was the glacier that disappeared during the melting when the interaction with extrusive melts took place.

Plateau-extrusions have ripples on the flat top which is proof of the lack of erosion from successive ice sheets. A lava flow occurred at the center or near the center of edifices. In this regard, it is assumed that magmatic channels of plateau-extrusions had a cylindrical form, and they were located at the intersection of faults. River valleys between the plateau-extrusions have a U-shaped profile.

Lava poured on pumiceous deposits. In some cases, the pumice lies on the top of the extrusive domes, as, for example, on Sopka Otkritaya. On the eastern slope near the summit of Geyzernaya plateau-extrusion, the block of layered pumices is located. They have different thickness throughout the Uzon-geyser depression. In outcrops of Geyzernaya River the pumiceous deposits have a thickness ~ 150-200 m. In the South-East they are rare. In the east of the Uzon-Geysernaya depression, pumices are covered with lava flows of the Bortovaya extrusion. Near the volcano Kikhpinych the thickness of those sediments decreases. The eastern edge of the Uzon caldera is surrounded by extrusive domes with sharp peaks. The height of these extrusions is less than that of the eastern extrusions. There are no lava flows there. For some extrusions in the upper Shumnaya River (Belaya Mountain) pumices of two types are characteristic: a) loose and poorly compacted pyroclastic pumices, and b) extrusive pumices "in situ" (Belousov, Ivanov, 1967).

Pumices in the valley of Geysernaya River are overlain on lacustrine deposits the formation of which is connected with the glaciers of the Uzon-Geyzernaya depression (age 20-35 thousand years). They are represented mainly by explosive deposits, among which there are layers of ash tuffs. The total thickness of the lacustrine deposits is 310 m. It is assumed that they are hyaloclastite that were deposited in a subglacial lake. The formation of these volcanogenic-sedimentary strata is associated with explosive activity which is directly connected with the formation of the Uzon-Geyzernaya depression. They were subject to low-temperature hydrothermal metamorphism (~100°C). This complex of rocks has the age about 40 thousand years. Lakustrine deposits lie above the pack of agglomeration, psephitic, psammitic and aleuritic tuffs with thickness of ~ 600 m. The age of these tuffs is the Lower and Middle Pleistocen.

The canyon of the rivers Shumnayay and Geyzernaya and streams flowing in them is the result of the erosion produced by powerful streams of melted water (see Fig. 2). Such flows are typical for Iceland in the areas of the interaction of volcanoes and glaciers (*jökulhlaups*). It is assumed that the deposits of such subglacial floods compose the Shirokoye plateau (Leonov, Grib, 1999).

4.0. HYDROTHERMAL ACTIVITY AND METAMORPHISM

The Old Kikhpinych volcano is composed mainly of lavas, tuffs of basalts and andesite-basalts. Young cinder cones and associated lavas have basaltic composition. The dacitic dome of Sopka Zheltaya also introduced in the final stage of the volcano activity (Fig.7).

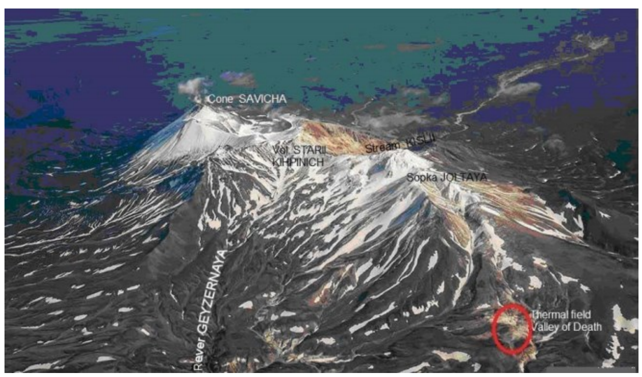

Figure 7: Kikhpinych long-life volcanic center. Brown color shows rocks altered by acidic thermal waters.

Clays of the Kikhpinych long-life volcanic center are the products of its hydrothermal activity. They can be seen in the thermal fields of the volcano Old Kikhpinych and extrusion Zheltaya Sopka. Springs at the Old Kikhpinych southern slope have the hydrocarbonate-sulphate composition and temperature up to 97°C, pH < 3. In the stream Kislii, the subalkaline sources of slightly mineralized chloride waters are present. There is gas-steam jet with the temperatures up to 97°C on the southern slope of Sopka Zheltaya. H_2S is present there. The rocks of this field are opal, alunite, kaolinite. The rocks of the Upper-Geyser field are kaolinite, illite, montmorillonite, goethite, sulfur, and opal.

Modern alterations of the rocks of Old Kikhpinych and Sopka Zheltaya are occurring in thermal areas. They is smaller than they were in the Upper Pleistocene, in the ice age. Glacial forms of erosion on the edifice of Old Kikhpinych and distribution of altered rocks on Sopka Zheltaya indicate that in the Upper Pleistocene here was a source of a glacier. As a result of interaction between transmagmatic fluids and those glaciers, a significant horizon of high-temperature acidic waters heated by steam was formed.

In the middle and lower part of the basin of Geyzernaya river there are two aquifer complexes. The upper complex consists of explosive-effusive rocks. It is an unforced aquifer of fissure-strata water. The layer of sintered scoria and dense lacustrine volcanic-sedimentary rocks below it play a role of a lower impermeable horizon. The chemical composition of these waters is of hydrocarbonate-calcium (or sodium). Their mineralization is 0.03-0.2 g/l and the temperature is of about 10°C. At the selected sites in the upper Geyzernaya river and on the left slope in the middle part of the valley, there are sources of sulfate waters with mineralization of 0,1—0,2 g/l and the temperature also not exceeding 10° C.

Water of the second complex located below is characterized by slow circulation. They come out to the surface along the valley of Geyzernaya River. The aquifer of pressure thermal waters is associated with tuffs of lakustrine deposits and fractured lavas and tuffs formed earlier than calders. Those high-temperature pressure waters rise to the surface under hydrostatic pressure and come out to the surface through cracks in the roof of impermeable horizon as geysers and boiling springs. The chemical composition of high-temperature water is chloride-sodium with mineralization of 1.8-2.2 g/l. The water temperature at the depth in the area of discharge reaches 150-180°C. The maximum temperature of thermal water rising from the magma chamber is estimated ~ 330 °C.

Location of the thermal manifestations of the Kikhpinych long-life volcanic center and Geyzernaya River allows us to suggest that the flow of high temperature water migrates from the volcano Kikhpinych to Geyzernaya river and further to the caldera of Uzon volcano (Belousov et al., 1984). Here it manifests itself in the form of springs and lakes. Chemical composition of the sodium-chloride thermal waters in the Uzon caldera is defined as $Cl_{96}/Na_{90}K_5$; pH 5-8. The concentrations of HCO_3 and SO_4 are negligible. Water has a high content of H_2SiO_3 – up to 400 mg/l. Spontaneous gas consists of (in volume) CO_2 - up to 75-95%, H_2S – up to 8%, CH_4 - up to 8% and N_2 -up to 5-25%. The outputs of chloride-sodium waters are usually bordered with sulfate-chloride and chloride-sulfate waters. These waters are characterized by high concentrations of As, Sb, Hg, Pb, Ag, Be, B, Li, Cs, Rb and other metals.

5.0. DISCUSSION

Bachmann O. and Huber C. (2016) made a review of studies of magmatic chambers located in the Earth's crust. It is established that those structures play a key role in the management of multiple processes of the Earth including magma differentiation, degassing, formation of the crust and volcanism. Despite significant achievements, the final understanding of the processes occurring in magma chambers in the Earth's crust is currently not achieved. The researchers propose the concept of the evolution of magma columns in the Earth's crust which is mainly due to the high crystallinity of magma (mush zones). It is presented as a model of Polybaric Mush (Bachmann, Huber, 2016). However, it is noted that there are many questions yet to be answered.

Thus, there is a need for further research of shallow (peripheral) magma chambers. This structure is being studied on the Kikhpinych long-life volcanic center on Kamchatka (Belousov et al., 1984).

It is known that the Kikhpinych hydrothermal-magmatic system located in the long-life volcanic center of the same name is controlled by anomalous heat flow. Due to this, heat flows are to determine the formation and evolution of crustal magma chambers that are part of this system. Belousov and others (2005) proposed a model in which the crust magma chamber generates thermal energy that in which a source generates thermal energy that supports the activity of the Kikhpinych magmatic-hydrothermal system.

It is assumed that at the embryonic stage of the Kikhpinych long-life volcanic center under conditions of the oceanic Earth's crust the ascending column of magmatic melts heats the aquifer complexes. In the process of interaction between water and rock, thermal water becomes saturated with H_2SiO_3, metals and gases. Among metals, the leading role belongs to iron. The interaction between siliceous hydrothermal solutions and seawater results in the formation of colloidal system (silica + sulphides). In places of discharge of submarine hydrothermal systems, silica and sulphide ores are deposited in the form of "black smokers" (Belousov et al., 2008).

In addition, the significant volumes of natural gas are produced as the result of biological synthesis (Botz et al., 1999). The biomass generated in the fluids of submarine magmatic-hydrothermal systems is a significant part of organic matter (McCollom, 2000). Thus, volcanogenic-sedimentary deposits with organic matter and sulphides are formed in the submarine magmatic-hydrothermal systems (Pirajno, 2009). Those deposits are capable of exothermic reactions (burning) in the areas of magma temperatures. Mantle convective heat flux is enhanced by additional thermal energy of those reactions. The heat in the crust magma chamber can accumulate only under conditions of minimal losses in the surroundings of the heat insulation and waterproof screens. Such screens can be sedimentary and metamorphic rocks which properties are continuously renewed in the process of self-organization. Accumulation of heat leads to a temperature rise and that contributes to the transformation of rocks with low melting point into the magma. This process contributes to the formation of peripheral magma chamber in the Earth's crust of the long-life volcanic centers.

Oxidation of sulfides and hydrocarbons produces free hydrogen (Giggenbach, 1976) that with the oxygen creates an explosive mixture capable of detonation explosions. The manifestations of detonation explosions are characterized by the presence of the funnel of the explosion (a mine crater) from the cylindrical channel characteristic of the jet expiration of two-phase media. In our opinion, an example of such an explosion crater is the craters of Krasheninnikov volcano from which pyroclastic flows were erupted (Fig. 8).

Figure 8: The annular ridges of the craters of the Krasheninnikov volcano.

During the eruption of pyroclastic flows (ignimbrites) the shock waves caused by gas explosions destroy the roof over the places of ignimbrite (migmatites) material generation with the formation of open tension joints in host rocks over a large area. Along those cracks the air enters the zone of explosions generation. In the centers of detonation explosions vacuum is created. It enhances the inflow of magma melts and its degassing which for CO2 begins at the depths of 25-40 km (Lowenstern, 2001). The emersion of increasing in volume of CO2 bubbles leads to a forced (pressure) convection and mantle melt injection in the cavities formed by the explosion. This vortex process mixes mantle and crustal magmas. Crust melts become heated, emit dissolved gases, and pumice is being formed (Fig. 9). This process results in the explosion.

Figure 9: The volcanic bomb composed of bands of different composition – the white stripes have rhyolite composition, black - basalt composition (Leonov, Grib, 2004).

5.1. Glaciation and transformation of the Kikhpinych hydrothermal-magmatic system

The Kikhpinych hydrothermal-magmatic system is the result of heat and mass transfer processes in the Earth's crust that are generated in the upper mantle. They are controlled by the thermal gradient of the system.

Geological evolution of the Semjachik geothermal area shows that its hydrothermal-magmatic systems are united by the thermal front (anomalous heat flow) which is generated by basaltic magma reservoir. From the Late Cretaceous to the Quaternary Period a volcanic island arc operated which crust converged under the weight of the edifices of submarine volcanoes. Volcanic formations were subjected to hydrothermal metamorphism, and the volcanogenic-siliceous formations were being created containing sulphides and organic carbon.

It is assumed that this heat flux had a capacity similar to the capacity of the modern abnormal flow of the rifts of Sredinny range in Kamchatka estimated as ~ 8000 kcal/km^{2}c. The surface heat flow of the Uzon-Geyzernaya depression is ~2000 kcal/km^{2}c (Belousov et al., 2017). Thus, in the depths of this area the thermal losses of ~6000 kcal/km^{2}c occurred, and they were implemented in the formation of long-life volcanic centers.

The main heat-transfer agents in hydrothermal-magmatic systems are magma and water which have a complex structure. The migration rate of the individual elements of these heat-transfer agents depends on their thermophysical properties. Volatile elements (gas, alkaline metals, etc.) migrate relatively faster than the mass of silicate melts under the same thermal gradients. They belong to trans-magmatic fluids (Belousov, Belousova, 2016).

Unlike fissure eruptions, stratovolcanoes are characterized by the constant activity (at the scale of geological time). It is assumed that this is due to the presence of shallow magma chambers in them which are accumulators and generators of additional quantity of heat. It is assumed that the excessive degassing is an evidence of the exothermic oxidation-reduction reactions ("burning") of sulphides and organic matter in the depths of hydrothermal-magmatic systems (Belousov et al., 2005; Shinohara, 2008).

Studies of modern hydrothermal systems show that their formation and activity is due to the presence of lithological screens ("cap-rock") (Belousov, 1967). Logically it is possible to assume that the formation of magma chambers is also associated with the presence of thermal screens. Such screens may be dense rocks which are dominated by the molecular conductivity. In addition, these horizons should have low permeability which restricts the inflow of cold meteoric water to the zones of magma chambers generation. On the Earth's surface such properties are common for glaciers and permafrost horizons. Belousov V. I. (1978) offered to choose the Koshelevsky type of hydrothermal systems, in which glaciers affect their formation and activity (Fig. 10).

The Kikhpinych system belongs to this type. In such systems, the descending acidic thermal water are being neytralized (Giggenbach, 1997), and the flow of chloride-sodium waters is being formed. This flow migrates to the Valley of Geysers and caldera of Uzon volcano. The water of this flow is saturated with dissolved silica. It is deposited in water-bearing complex. The water-bearing complex is transformed in poorly permeable horizon with a thickness of ~ 2-3 km. It plays the role of the screen for the ascending heat flow. There is an increase in temperature and partial melting below the horizon accompanied by the formation of migmatites *in situ* (Gue-Neng Chen, Grapes R., 2007). Trans-magmatic fluids accumulate under this screen. They contain a significant amounts of CO_2, H_2 and alkali metals (Belousov et al., 2017).

Ascending mantle melts intrude into the zone of partial melting. Degassing and eruption occur. Ring faults or caldera are formed around the eruptive columns. Expulsion of trans-magmatic fluids with CO_2 from the mantle melts substantially lowers the level of degassing down to the upper mantle (Belousov et al., 2017). This gas lift evacuates a huge mass of heterogeneous material from the depths of ~ 3-10 km. Huge pyroclastic flows are formed. In the presence of the glaciers they spread to large areas (ignimbrite). It is assumed that the concentrations of volatile components in the zones of selective melting are distributed irregular that is why the textures of the rocks vary. When CO_2 which has low thermal capacity is excess, melt keeps the temperature and is able to sinter. So fiamme can be formed, when CO_2 is removed from the foam part of the melt ("pumice"). If there is H_2 (5%) in the accumulated gases, the formation and detonation explosion of the "explosive mixture" is possible under conditions of phreatomagmatic eruptions. Grebenshchikov (2004) showed that the Jakutiskiu ignimbrites were formed this way. During the degassing of water vapor from the melt, solid pumice are formed due to the large thermal losses as the enthalpy of steam is high (700-1000 kcal/kg).

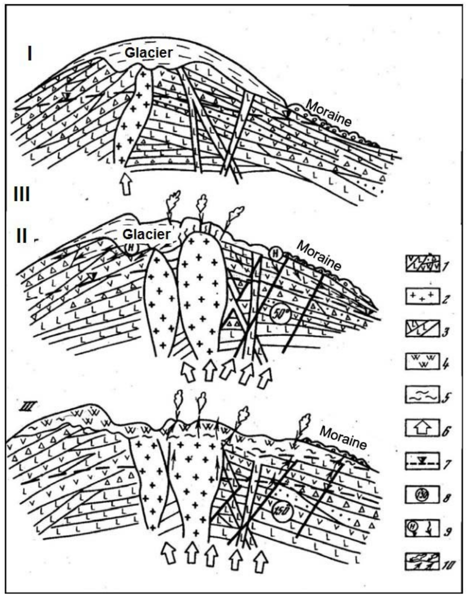

Figure 10: Stages of development of the Koshelevsky type hydrothermal system. I – introduction the volcano extrusive dome; II - the interaction between an extrusion and glacier; III – formation of the hydrothermal system; 1 - volcanic structure; 2 - extrusion; 3 - dykes; 4 - opal rocks; 5 - clay; 6 – anomalous heat flow; 7 - groundwater level; 8 – water temperature; 9 - acidic water; 10 - steam and gas.

5.2. The evolution model of the magma chamber of Kikhpinych hydrothermal-magmatic system

In the Upper Quaternary period, the Kikhpinych volcano was the area of the supply for the glacier. Its thickness reached a few hundred meters. The western branch of the Kikhpinych glacier extended over the tectono-magmatic fault along which the introduction of mantle basaltic melts occurred. Glaciers and permafrost horizons restricted the infiltration of meteoric waters into the hydrothermal-magmatic system. They also played the role of a heat insulation complex. Below it the heat transported by the Kikhpinych magmatic-hydrothermal system accumulated. The result was the extension of the induced thermal field the temperature of which near this system was sufficient for the selective melting of rocks and hydrothermal processes. Those areas reached the thermal readiness for the interaction with injections of high-temperature basaltic melts which manifested themselves in intense degassing and explosive activity of rocks and selective melts of migmatites type.

After the explosive evacuation of the selective melting material there is the intrusion of high-temperature basaltic melt which fills the vacated space. The effusion of huge pyroclastic flows and intrusion of mantle melts occur almost simultaneously. At this time, the basalt column creates a large pressure gradient which leads to degassing of CO_2 in the upper mantle. This influx of mantle melts affects the overall rise of the above lying structures and heat transfer to the siliceous horizon by high-energy trans-magma fluids. The presence of alkali metals in these fluids is confirmed by their increased content in extrusive rocks. Mantle H_2S in the aquifer complex of chloride water leads to the formation of sulphides which along with colloidal silica (silica gel) migrate as a mixed colloidal system and are deposited in the caldera of Uzon volcano (Belousov et al., 1998). Melting of the siliceous horizon leads to the formation of acidic magmas. Mixed melt saturated with mantle gases and water vapor erupts in subglacial meltwater lakes. The low permeable lacustrine sediments of the Uzon-Geysernaya depression, glacier and siliceous rocks play the role of a heat insulator and unpermeable layer (cap rock) in the Kikhpinych magmatic-hydrothermal system. Under the pressure of molten rock, degassed mixed melt squeezes out to the surface (Fig. 11). The cooled extrusions, faulted by cracks, are the structures that result in the downward filtration of meteoric water in the magma chamber (Farrar et al., 2003). After the glaciers vanished, the chamber shrank and its western boundary is approaching the edifice of the volcano.

It was noted above that the development of the magma chamber happened in a south-western direction along the latitudinal fault (Fig. 1). There are no indications of its expansion to the east. There may be the flow of acid water heated by steam in the direction to the ocean. However, the thermal manifestations similar to the opposite direction are not found. It is assumed that the acidic thermal water of this flow became neutral near the Kikhpinych volcano and was mixed with sea water. The warm and waterproof barrier was formed as a result of the deposition of dissolved silica from chloride thermal waters (Belousov et al., 1998).

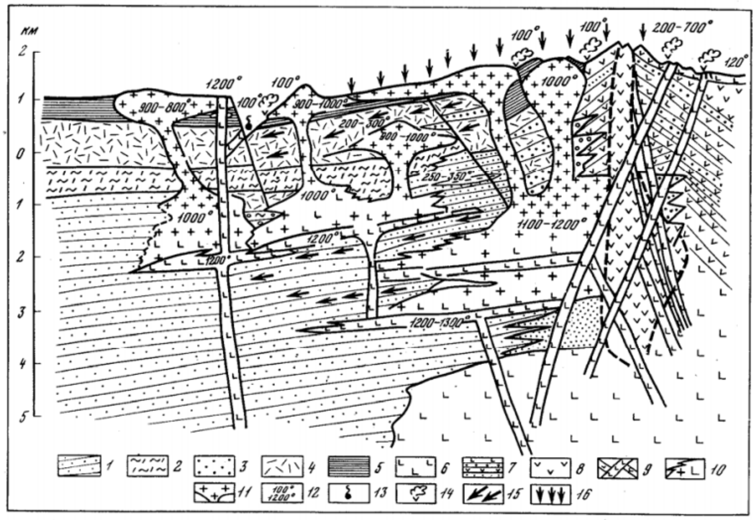

Figure 11: Schematic geological section of the high-temperature hydrothermal system and Kikhpinych long-life volcanic center (Belousov, 1978). 1 — fine-clastic volcanogenic-sedimentary strata (waterproof beds); 2-ignimbrites; 3-4 - medium - and coarse-grained facies of volcanogenic-sedimentary strata; 5 — siliceous and dense volcanogenic-sedimentary strata; 6 — basalts; 7-8 — lava-pyroclastic deposits; 9 — dikes and sills of basalt; 10 — zones of mixing of basaltic melt intrusions with formation of a secondary melt of heated volcanogenic-sedimentary host formations; 11 — extrusion of acid composition; 12 — temperature; 13 — ascending thermal springs; 14 - gas jets; 15 — the direction of hydrothermal flows movement; 16 — direction of meteoric waters filtration.

The disappearance of glaciers and extrusions resulted in the formation of a strong downward flow of meteoric waters. This contributed to the hardening of the peripheral part of the magma chamber and reducing of the horizontal heat flux. Basaltic cones with lava basalts on the edifice of the Old Kikhpinych suggest that mantle melts intruded through the parts of the magma chamber which were already cooled.

Modern glaciers influenced the formation and evolution of acidic magma chambers of the Ichinsky stratovolcano in Sredinny Renge in Kamchatka. There is a glacier on its top (Fig.12).

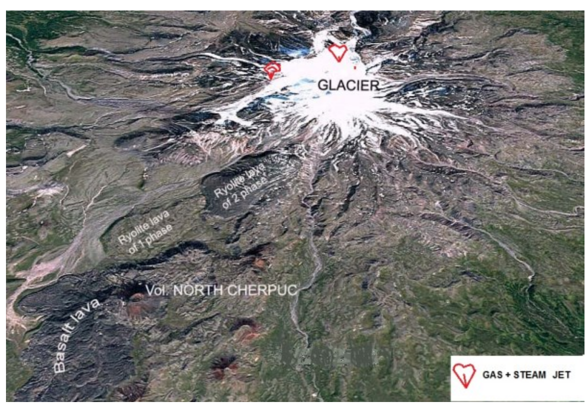

Figure 12: Ichinsky volcano. Kamchatka (see text).

Even in the Holocene, its area was much larger and reached the foot of the edifice. The activity of the volcano began with eruption of lavas and basal tuffs and andesites in preglacial time. It was interrupted by Middle and Upper Pleistocene glaciation. After the retreat of glaciers, the products of new eruptions, represented by rhyolite and dacite ignimbrite, were deposited in trough valleys (Marenin, 1961). In the Holocene, acid lava flows with a well preserved wavy surface poured out on the slopes of edifice between the troughs. At the south-western sector of the bottom of the edifice, cinder cones with lava basalts also were formed in the Holocene.

In our view, the evolution of rhyolite-dacite magma chamber of the Ichinsky stratovolcano is as follows. On the top of this volcano a modern glacier of considerable thickness is located. There is a rhyolite dome under the glacier, with gas-steam jets indicating that the horizon of acidic thermal waters heated by steam is forming under the glacier. As the volcano has a height of more than 3500 m, descending acidic thermal waters become neutral. They form a flow of chloride-sodium waters which deposit silica in water-bearing complex of rocks considerably below the base of the volcanic edifice. The injections of basaltic melts, which presence is indicated by cinder cones with lava flows, are screened by siliceous complex which is melting. It is assumed that two generations of rhyolite lava flows in the middle of the volcanic slopes are evidences of the retreat of the glacier and the rise of the magma chamber roof.

CONCLUSIONS

The geothermal concept of the magma chambers of stratovolcanoes located at a small depth offers an original explanation of some problems of their formation and evolution.

1. The formation of such structures is due to the self-organization of an anomalous heat flow. The convective heat flux forms a hydrothermal-magmatic system which is implemented in the form of a long-life volcanic center.

2. In this center, there is an interaction between thermal energy transported by a complex mantle heat-transfer agent and water in the Earth's crust and carrying it out to the Earth's surface.

3. The activity of hydrothermal-magmatic systems depends on the sources of heat generation and heat loss.

4. As the crust thickens, there is a need for an additional heat source and limiting of heat losses, especially near the Earth's surface.

5. This is ensured by hydrothermal metamorphism processes forming a medium capable of generating heat energy and the system for its conservation.

6. In this system, glaciers play the role of a factor regulating the downward flow of meteoric water into the long-life volcanic center.

7. The heat losses of the island arc volcanoes in tropical latitudes are limited by formations of organogenic sediments (Belousov, Belousova, 2012).

8. It is assumed that the peripheral chambers of submarine volcanoes of mid-oceanic ridges and oceanic islands can be formed with the participation of the screens presented by horizons of serpentinite or sheeted dyke complexes. The volcanoes of island arcs, where there are no glaciers, are topped by the hydrothermally altered rocks. They are formed as a result of the interaction between basalts and andesites of the edifice with acidic thermal waters. Such hydrothermal fluids can be generated during the interaction of wet fogs and volcanic gases.

REFERENCES

Bachmann, O. and Huber, S. Silicic magma reservoirs in the Earth's crust, *American Mineralogist*, Vol. 101, No. 11, (2016), 2377-2404.

Belousov, V. I. Role of geologic-structural factors in formation and activity of hydrothermal systems within volcanic recent regions. Dissertation Autoreferat of candidate of geologic-mineralogical science Petropavlovsk-Kamchatsky, (1967) (in Russian).

Belousov, V. I. Geology of geothermal fields in the areas of modern volcanism. M.: Nauka, (1978) (in Russian).

Belousov, V. I., Ivanov, V. V. Pumice Formations in the area of Uzon Depression. Geisernaya River Valley in Kamchatka, *Bull. Volcanolo*g., (1967), Tome 30, 75-79.

Belousov, V. I., Grib, E. N. and Leonov, V. L. The geological setting of the hydrothermal systems in the Geyzer Valley and Uzon caldera, *Volcanology and. Seismology*, (1984), Vol. 5, 67-81.

Belousov, V. I., Rychagov, S. N., Faslullin, S. M., Kuzmin, Yu., Isidorov, V. A., Belousova, S. P. Silica in high-temperature hydrothermal systems of the areas of modern volcanism, *Ecological chemistry*, (1998), T. 7, Vol. 3, 200-216 (in Russian).

Belousov, V. I., Rychagov, S. N., Kuzmin, Yu., Belousova, S. P. Hypothesis on the origin of the crustal heat source in the hydrothermal-magmatic convective systems, *The field materials of the International Kuril-Kamchatka workshop*, July 16 – August 6, (2005), 153-170 (in Russian).

Belousov, V. I., Rychagov, S. N., Belousova, S. P., Filippov, Y. A. To the question of the origin of mineral complexes "black smokers", RMS DPI 2008-2-6-0 (in Russian).

Belousov, V. I., Belousova, I. V., Filippov, Yu. et al. The formation of hydrothermal-magmatic systems of skarn type, Proceedings, Thirty-Seventh Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, January 30 - February 1, (2012) SGP-TR-194.

Belousov, V. I., Belousova, I. V. Heat Transfer in Hydrothermal-Magmatic Systems, Proceedings, 40th Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 22-24, (2016), SGP-TR-209.

Belousov, V, Erlich, E., Kuzmin, Yu. Geotectonics and Heat Flows, Proceedings, 42nd Workshop on Geothermal Reservoir Engineering Stanford University, Stanford, California, February 13-15, (2017) SGP-TR-212

Botz, R., Winckler., Bayer R., et al. The origin of the trace gases in submarine hydrothermal vents of the Kolbeinsey Ride, north Iceland, Earth. Planetery Sc. Letters, (1999), V. 171 (1), 83-93.

Chaimowicz, V. S. Ignimbrites of Kamchatka. M.: Nedra, (1979).

Erlich, E. N., Melekestsev, I. V., Braitseva, O. A. Evolution of Recent Volcanism, Bulletin of Volcanology, (1979), Vol. 42, No. 1-4, 93-112, doi: 10.1007/BF02597042.

Farrar, C. D., Sorey, M. L., Roellfs, E., Galloway, D. L., Howle, J. F., Jacobson, R. Inferences on the hydrothermal system beneath the resurgent dome in Long Valley Caldera, east-central California, USA, from recent pumping tests and geochemical sampling, Journal of Volcanology and Geothermal Research, 127, (2003), 305-328.

Giggenbach, W. F. Variations in the carbon, sulfur and chlorine contents of volcanic gas discharges from White Island, NewZealand, Bull. Vol., (1976), V. 39 (1), 15-27.

Giggenbach, W. F. The origin and evolution of fluids in magmatic-hydrothermal systems, in Barnes, H. L., Geochemistry of hydrothermal ore deposits, 3rd edition: New York, John Wiley, 737-796.

Grebennikov, A.V. The ignimbrites of the Petrogenesis of Yakutensky volcanic structure, Autoreferat, The dissertation on competition of a scientific degree of candidate of geological - mineralogical Sciences, Vladivostok, (2003), (in Russian).

Gudmundsson, A. Infrastructure and mechanics of volcanic systems in Iceland, Journal of Volcanology and Geothermal Research, (1995), No. 64, l-22.

Gue-Neng, Chen, Grapes, Rodney. Granite genesis: in situ melting and crustal evolution, Springer, (2007).

Kugaenko, Yu. A., Saltykov, V. A., Gorbatikov, A.V., Stepanova, M. Yu. The development of a model district of the Uzon-Geysernaya depression and volcanotectonics around Kikhpinych volcano (Kamchatka) according to the results of a joint analysis of data of microseismic sounding and local geodynamic activity, Physics of the Earth, (2015), No. 3, 89-101 (in Russian).

Leonov, V.L., Grib, E.N. Calderas and Ignimbrites in the Uzon-Semyachik Area of Kamchatka: New Data from Field Work on the Shirokoe Plateau, Volcanology and Seismology, (1999), V.20, 299-320.

Licciardi, J.M., Kurz, M.D., Curtice, J.M. Glacial and volcanic history of Icelandic table mountains from cosmogenic 3He exposure ages, Quaternary Science Reviews, 26, (2007), 1529–1546.

Lowenstern, J.B. Carbon dioxide in magmas and implications for hydrothermal systems, Mineralium Deposita, (2001), 36, 490-502

McCollom, T. M. Geochemical constraints on primary productivity in submarine hydrothermal vent plumes, J. Deep Sea Res., Part 1: Oceanographic Res., (2000), V. 47, No.1, 85-101.

Naboko, S. I. Volcanism, hydrothermal process and ore formation, Nedra, Moscow, (1974), (in Russian).

Ohsawa, S., Yusa, Y., Oue, K. Amita, K. Entrainment of atmospheric air into the volcanic system during the 1995 phreatic eruption of Kuju Volcano, Japan, Journal of Volcanology and Geothermal Research, 96: (2000), 33–43.

Pirajno, F. Hydrothermal Processes and Mineral Systems , chapter 7 Submarine Hydrothermal Mineral Systems, Springer, Geological Survey of Western Australia, (2009), 581- 726.

Russell, J.K., Edwards, B.R., Porritt, L., Ryane, C. Tuyas: a descriptive genetic classification, Quaternary Science Reviews, (2014), No. 87, 70-81.

Shinohara, H. Excess degassing from volcanoes and its role on eruptive and intrusive activity, Rev. Geophys., (2008), 46, RG4005, doi:10.1029/2007RG000244.