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Heat Transfer in Hydrothermal-Magmatic Systems

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ABSTRACT

To increase the efficiency of heat extraction for industrial purposes the researchers are looking for a supercritical heat transfer medium (Fridleifsson et al., 2011). The deep well in Kakkonda H-MS made a transition from the hydrothermal convection cell to the hot igneous intrusion (Tamanyu, Fujimoto, 2005). Dunn and Hardee (1981) proposed the concept of the existence heat transfer with thermal parameters above critical in the hydrothermal-magmatic system zone with vigorous convection. However, such heat transfer medium was never obtained in the hydrothermal-magmatic system, where the drilling of geothermal wells was made. The maximum temperatures in those wells only reach critical values. Nevertheless, in the stationary columns of magma (extrusion) powerful jets of gas and steam (fumaroles) in the central volcanoes exist for a long time (tens - hundreds of years) indicating a powerful convective heat flow in the magmatic convective cell (on Kamchatka volcanoes Avachinsky – 60 000 kcal/s; Mutnovsky - ~400 000 kcal/s respectively). These and other data suggest that the problem of transporting large quantities of thermal energy in hydrothermal-magmatic system, which are observed in nature, is still not resolved. However, there is no doubt that the significant heat flows in magma act as a link between magmatic and hydrothermal cells. Thermophysical properties of sodium and potassium are typical for the magmatic-hydrothermal process. Sodium and potassium can be transported from the upper mantle to the Earth's surface at a significant rate due to the temperature difference these elements. These assumptions are confirmed by the composition of gases containing large amounts of metals, and sublimates around outputs of the superheated steam-gas jets. The evacuation of the volatile components creates conditions for their mobilization from magmatic chambers and along the entire length of the hot dyke characterized by large heat losses, resulting in the huge temperature gradient. Since alkali metals are characterized by large heat content and significant concentrations in the melt, they can play an important role in heat-and-mass transfer. Volatile components can create elevated concentrations in the head of the magmatic column and heat the sections of the host rocks, preparing the way for advancing successive portions of a magmatic melt. Undoubtedly, the magmatic gases participate in the processes of convective heat and mass transfer. According to the data obtained in the study of physical chemistry of pyrometallurgical processes, these gases are in a balance with a multi-component melt. According to the studies of the natural and artificial systems, when gases included in the composition of the melt pass through the complex processes of the chain reactions, they are converted to water vapor, HS-legislate and other gases. Alkali metals have a great influence on the chain reactions of gases. They affect the decrease in the temperature of the gaseous elements ionization and the increase in the internal energy of the volatile phase in magmatic melts. As mentioned earlier, the movement of the magmatic volatile phase of the melt is determined by the temperature pressure in the magma conducting structure. Heat losses in its upper part may control the flow of the heat transfer medium, in particular, alkali metals, and the heat flow from the upper mantle. Thus, the intensive extraction of the geothermal fluid of the hydrothermal convective cell of H-MS can be stimulated, but it should be controlled to prevent excessive heating of the magmatic convective cell which can cause a volcanic eruption.

1. INTRODUCTION

Sources of heat and mechanisms of its transmission are the important problems of hydrothermal processes and ore-forming systems. In the areas of active volcanism and hydrothermal activity, anomalous heat flows are caused by the convection in hydrothermal-magmatic systems. Convection is provided by the movement of the heated masses of substances with a high thermal capacity (heat transfer medium). In geology it is traditionally considered that water and magma are the main heat transfer media. The heat source is magma. The hydrothermal-magmatic system is composed of magmatic and hydrothermal convective cells. It is assumed that in the transition zone heat is transported either by the conductive (molecular) heat flow through a layer of dense rocks (Banwell, 1964) or by the water fluid with parameters above the critical (Averiev, 1967).

2. THERMAL SUPPLY OF THE ACTIVE HYDROTHERMAL SYSTEMS

In the early 1900s, it was thought that hydrothermal ore systems were formed from magmatic chambers emanations (Lindgren, 1933). Later the concept of the large influence of meteoric water was suggested. It was confirmed by the studies of hot springs and stable isotopes of active and extinct hydrothermal systems. The problem of heat supply in the active hydrothermal systems was studied by Averiev V. V. (1967). He came to the conclusion that the values of the heat flow in geothermal areas were tens or even hundreds times higher than the average values of the Earth's regional heat flows. It was also assumed that at the base of the hydrothermal systems the temperature did not exceed 400° at a depth of 3 km and the pressure was not higher than 300 ATM. The granitic magma temperature in the Earth's crust may be 600 to 1000°C, which corresponds to the pressures 900-3900 ATM. Under such pressures the granitic magma may contain 3-7 wt. % of water. Thus, water in the amount of 5% of its mass does not separate from the magma. Water separation from magma is possible at high pressure, when magma is supersaturated with water or water fluid migrates through the magmatic melt. Therefore, Averiev V. V. (1967) believed that the formation of thermal anomalies in the Earth's crust in the geothermal areas is caused by the supercritical fluid. In general, its generation is not associated with local igneous bodies, but is a result of an independent process. In hydrothermal-magmatic systems, the magmatic bodies play the passive role of the magmatic fluids conductors.

Basing on the study of the isotopic composition of water, Craig H. (1963) came to the conclusion that magmatic fluids had a minor involvement in the formation of hydrothermal systems in the areas of active volcanism.

Giggenbach W. F. (1997) proposed a model for the origin of magmatic fluids from seawater in subduction zones. Dunn and Hardee (1981) developed the concept of the existence of the heat transfer medium with thermal parameters above critical in the H-MS zone with vigorous convection.

The deep well (3100 m) in Kakkonda magmatic-hydrothermal system (Japan) was drilled through the zone of the transition from the hydrothermal system to crystallizable magmatic intrusion (Fig. 1) (Tamanyu, Fujimoto, 2005).

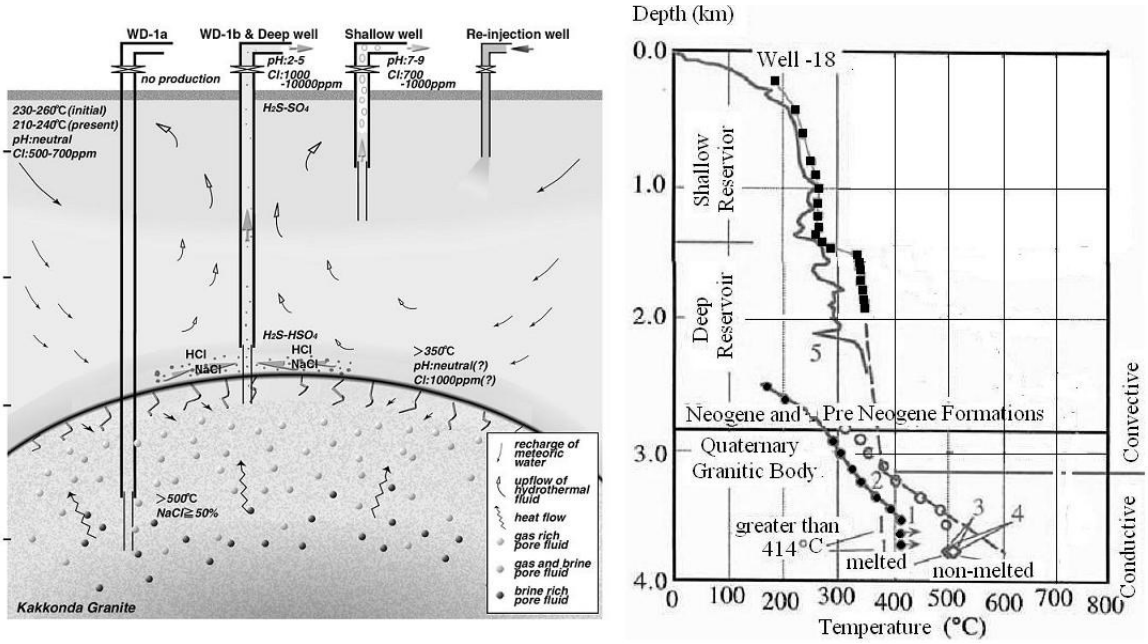

Figure 1: Schematic model of the magmatic-hydrothermal system of Kakkonda and temperature profile in a deep exploration well WD-1a (Tamanyu, Fujimoto, 2005).

At this depth the horizon is an equivalent of the near-surface isotherm 380ºC.

For industrial purposes the search for a supercritical heat transfer medium is being conducted (Fridleifsson et al., 2011). In 2009 the deep well (2.1 km) was drilled at the Krafla volcano in Iceland. The well was drilled into rhyolitic magma with a temperature of 900ºC. The steam from the well has a temperature of 380°C.

Currently, the highest temperatures obtained at the magmatic-hydrothermal systems were near-critical, i.e. below the temperature of magmatic melts and expected supercritical fluids. However, under conditions of not moving magma powerful fumaroles in the central volcanoes (Avachinsky – 60 000 kcal/s; Mutnovsky - ~400 000 kcal/s, Kamchatka, Vakin and others, 1976) exist for a long time (tens and hundreds years). These and other data suggest that the problem of transporting a large amount of heat energy in hydrothermal-magmatic systems is still not solved.

3. HEAT TRANSFER IN HYDROTHERMAL-MAGMATIC SYSTEM

3.1 Heat Transfer in a Hydrothermal Cell

The processes of heat migration, accumulation and dissipation are most thoroughly studied for hydrothermal conditions. As shown above, thermal energy transportation in the hydrothermal cell of the hydrothermal-magmatic system mainly occurs as a result of the heated mass migration. It is controlled by anomalous heat flows that are significantly higher than the regional heat flow. The movement of the heated masses caused by a gradient of temperatures happens towards low temperatures according to the second law of thermodynamics. There are two types of convection: (1) free convection - when the fluid motion is generated by density differences in the heat transfer medium (buoyant force) and the environment and (2) forced convection - when the fluid motion is generated by an external source.

Free convection occurs in the thickness of an aquifer which is in a liquid state. However, uneven heat supply of the aquifer causes its differentiated thermal structure characterized by thermo-artesian pressure (Elder, 1968). If the piezometric level of the hydrothermal cell is above the Earth's surface, the thermal water discharge is carried out by an ascending flow. In the discharge sites of hydrothermal flows, forced convection is manifested on the background of free convection in the hydrothermal cell and is controlled by the temperature profile. The temperature profile is close to the boiling point gradient relatively to the depth of the piezometric surface located near the Earth's surface (Fig. 2).

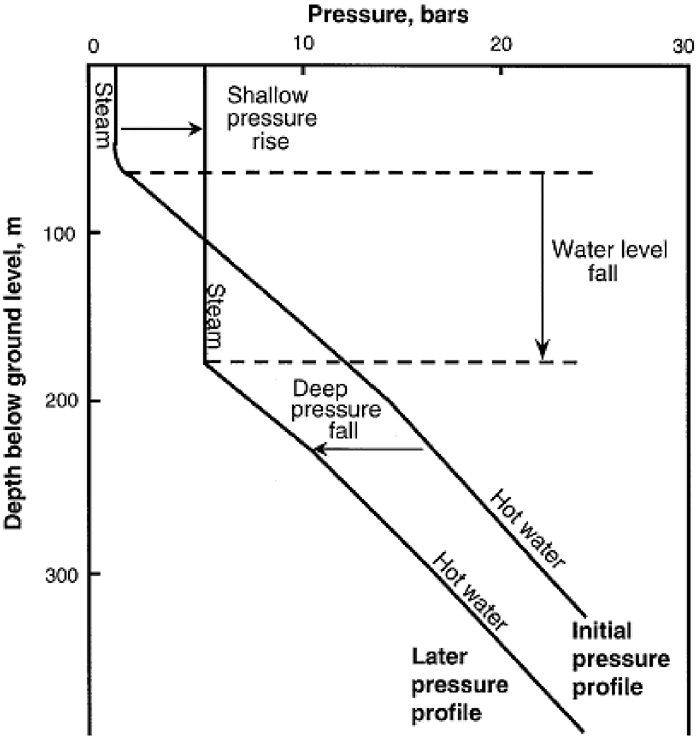

Figure 2: Pressure–depth relations in a hydrothermal system, showing that a decline in water level and a drop in deep shallow pressure can cause pressures to rise due to the formation of a steam zone (Browne, Lawless, 2001).

If the hydrothermal system is in the undisturbed state, hydrothermal eruptions will not occur. But even a very slight pressure drop at any depth can initiate subsurface boiling which may trigger a hydrothermal eruption. This process was studied in detail by Browne and Lawless (2001). There are several types of eruptions in hydrothermal-magmatic systems: geyser, hydrothermal (phreatic) and magmatic-hydrothermal (phreatomagmatic) eruptions.

A pressure drop could be the result of subsurface hydraulic fracturing, or local tectonic dilatancy, or be caused by removal of overburden through erosion, landsliding, draining of a lake, or lowering of the water table due to the dry weather. Heat transferred by magma into an active geothermal system could trigger a large eruption. Magmatic gases are the cause of boiling and eruptions. Concentration of gases in hydrothermal fluids increases the energy of the eruption.

Hydrothermal and magmatic-hydrothermal eruptions are caused by the interaction of several factors. An upper impermeable horizon (caprock) plays an important role in the formation of the bicarbonate thermal water shallow horizon. In which diffusive flux of CO_2 dissolves. When concentration of CO_2 reaches the supersaturation, a gas phase of CO_2 is formed. Gas bubbles rise up to the top of the hydrothermal-magmatic system. CO_2 gas stimulates boiling of the high temperature water at a depth of about 2.0-2.5 km, where gas-steam jets are formed. This gas mixture contains gases capable of detonation explosion (H_2, CH_4, CO, etc.) and chemically active gases (HCl, HF, SO_2, etc.). The latter form heated by steam acid water which contributes to formation of local rock horizons impenetrable for such gases. They can be mixed with atmospheric air in the jet of a gas-steam mixture, and that may be accompanied by a detonation explosion (Ohsawa et al., 2000). In our opinion, this mechanism is manifested in the formation of diatremes (Rychagov et. al., 2009).

Depth is controlled by their boiling temperature. Hydrothermal eruption, primarily begin at the surface and dive to the depths of the water reservoir (Fig. 3).

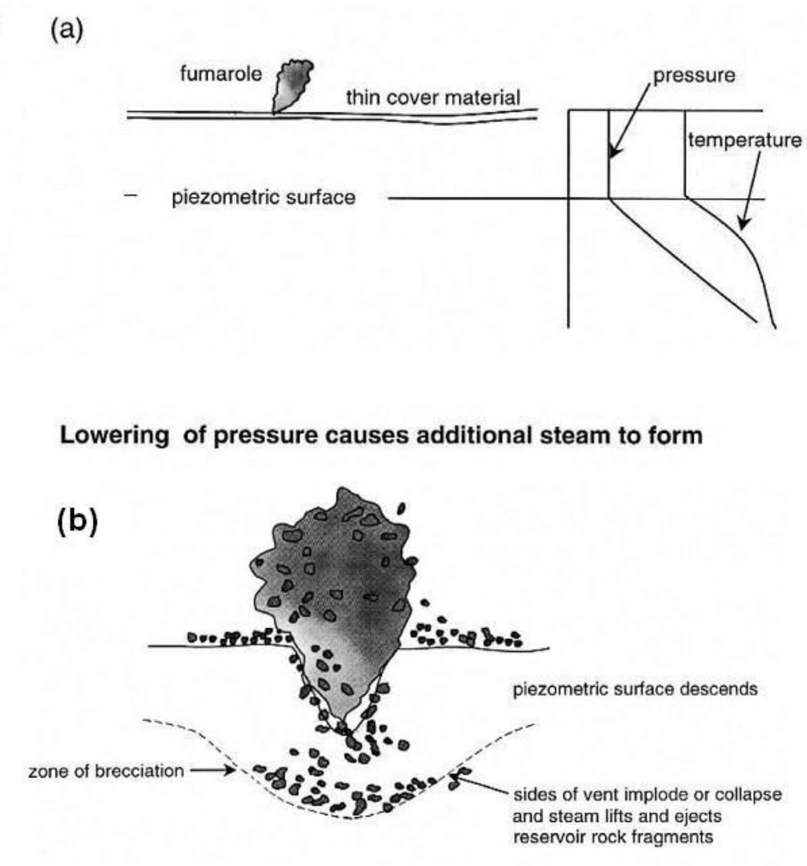

Figure 3: The development of a hydrothermal eruption and change in position of its piezometric surface. Vertical scale may be from 5 to 300 m (from Browne, Lawless, 2001)

The maximum depth of rocks destruction in the eruption channel depends on the physical properties of host rocks, piezometric water level, inflow of cold meteoric water and host rocks temperature which is about the boiling point of water. In our opinion, the trigger mechanism of hydrothermal eruptions is similar to the mechanism of self-organizing eruptions of geysers. Averiev V. V. and Sugrobov V.M. (Pauzhetski Hot Waters on Kamchatka, 1965) believed that in the geyser regime the eruption of the steam-and-water mixture occurs periodically. Usually the eruption begins with the discharge of water, slightly chilled at first, then more and more hot. At this stage the behavior of the geyser is no different from the behavior of the ordinary (not boiling) hot springs. Water discharge is small. Then from the geyser's vent water is released which is followed by the formation of a large vapor bubble. Water ejections become frequent, and then they go into a powerful explosion. It begins with the release of a large water plug, followed by a fountain of steam-and-water mixture. It acts short time. After that there comes the stage of steaming. The geyser stops its visible activity. After steaming, water fills the geyser's vent. In these cases, the thermal water level becomes stationary, but there is the movement of water in the channel. It is contributed by intense vertical convection which stimulates the boiling of water and spouting.

Thus, heat flow to the hydrothermal cell is an external source of the influence on aquifer. As a result, the aquifer temperature increases to values close to the boiling point. Heat balance in a hydrothermal cell is controlled by the heat flow from magmatic cell, or is a result of dissipation of heat by magma, or hot intrusion due to the heat conductivity or the heat transport flying phase along the channels of hydrothermal and hydrothermal-magmatic eruptions (diatremes).

Buttinelli et al. (2011) studied the magmatic-hydrothermal eruptions (formation of maars) in the Sabatini volcanic complex which is the part of a K-alkaline magmatic province. They proposed a model of formation of the Baccano maar which shows the evolution of the hydrothermal-magmatic explosion (Fig. 4).

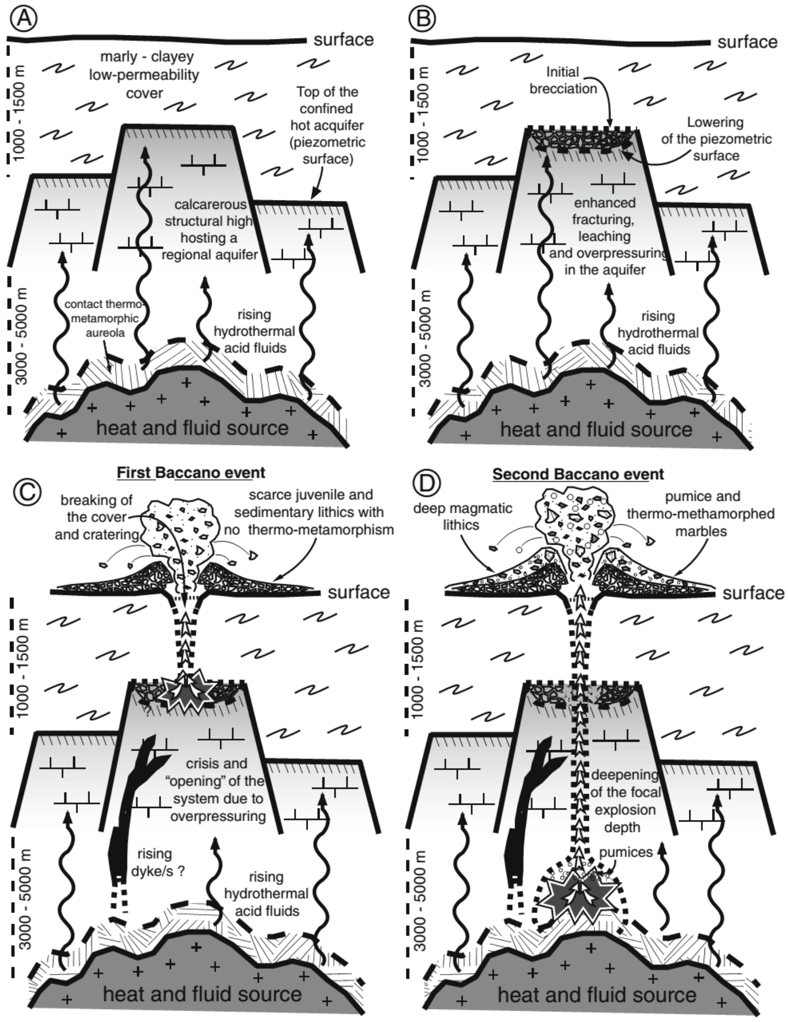

Fig. 4. Schematic representation of the evolution of Baccano maar activity: a structural setting of the area in the pre-eruptive stage; b initial stage of interaction between the rising hydrothermal acid fluids and the calcareous structural high hosting the regional aquifer; c First explosive activity of Baccano maar, characterized by an hydrothermal-phreatic eruption occurred involving the upper part of the confined aquifer on top of the structural high, with a no water–magma interaction. d Second explosive activity of Baccano maar, characterized by a more evident phreato-magmatic behaviour of the eruption, showing efficient water–magma interaction, which is accompanied by the deepening of the explosive focal depth (and/or a potential northward shifting of the crater) involving the thermo-metamorphic contact aureole of the magma chamber (Buttinelli et al., 2011)

In our opinion, the existence of such processes in magmatic-hydrothermal systems is confirmed by "quiet" eruptions of some volcanoes in Kamchatka and the Kuril Islands which occurred without strong seismotectonic events. Weak seismic events are generated in the edifices of volcanoes (Senyukov and others, 2006; Kugaenko, Nuzhdina, 2010; Kotenko, Igor, 2009). For example, a large number of historical eruptions of Avacha Volcano are explosive eruptions (hydrothermal explosions?). Only two eruptions (1894-1895 and 1991) were effusive-explosive (hydrothermal-magmatic?). The thermal power of the volcano between eruptions is estimated at 60000 kcal/s (Avacha Volcano, http://www.kscnet.ru/ivs/volcanoes/avach.html).

Giant eruptions of the central andesitic volcanoes due to sector collapse (Bezimjanniy on the Kamchatka Peninsula, St. Helens in the USA, Pinatubo in the Philippines and El Chichón in Mexico), in our opinion, may be caused by the explosions of hydrothermal-magmatic systems.

3.1 Heat Transfer in a Convective Magmatic Cell

3.2.1. The structure of the magmatic cell and anomalous heat flows.

Heat flows and heat concentration in the Earth's crust and upper mantle supply magmatic activity with energy. Magmatic processes are mainly caused by convective mass transfer produced by magmatic melts with complex composition. Heat migration contributes to the formation of the geological structures that move magma to the Earth's surface. Geological structures of volcanic regions have an effect on the heat transport, its transformation and accumulation which causes the formation of magma chambers and reservoirs. It is assumed that the anomalous heat flows in the magmatic zones may vary in space and time. Such transformation affects the types of volcanism (areal, fissure, central), the depth of magmatic chambers, types of magma and eruptions. The presence of insulating structures is a cause of heat accumulation which is accompanied by temperature increase, rocks melting and formation of magma chambers and reservoirs at the base of the insulator. The lift of the insulating horizon base focuses high-temperature igneous melts. The highest convective heat flow occurred in the central volcanoes during eruptions. Here, the heat flow depends on the heat carrier (gaseous, the hypothetical "plasma" or heated lava) (Sviatlovski, 1971). Many of the volcanic systems of Iceland are central volcanoes which have shallow magma chambers. These chambers act like a trap for magma and ascending dikes from the mantle reservoir (Fig. 5).

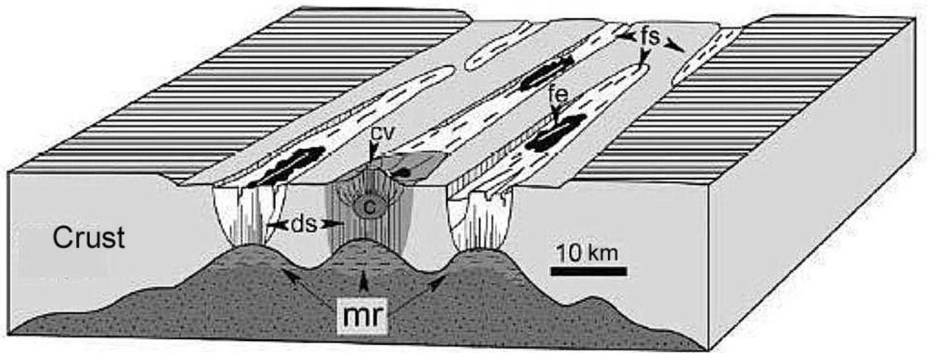

Figure 5: Schematic illustration of the presumed magmatic chamber and reservoirs beneath the volcanic systems in the rift zone of Iceland, ds — dike swarms, C — crust magmatic chamber, mr - magmatic reservoir, cv - volcano of the central type, fe — fissure eruption, fs – swarm of fissures (Jóhannesson and Sæmundsson, 1998).

Focusing of magma on a plot of a limited size makes a melt flow into chambers and reservoirs formed during the melting of host rocks. This process is the main reason of the formation of central volcanoes in volcanic systems. Melting of host rocks is one of the main processes resulting in the self-organization of magma chambers and reservoirs. It is determined by partial melting and accumulation of sufficient heat for this process (Gudmundsson, 1995). In addition, the formation and activity of magma chambers and reservoirs in the magmatic cell contribute (due to the redox reactions (chemical heat reactors)) to the generation of heat which is necessary to maintain operating conditions of the magmatic cell. The accumulation of thermal energy in the Earth's crust is apparently the result of melting of more fusible rocks. It may be the horizons transformed by hydrothermal processes.

Eruptive channels of central volcanoes provide multiple eruptions of magmatic melts. A large part of fissure volcanoes are active only once. Sometimes fissures can open a few times. The mechanism of opening of these channels is unclear. Many dikes intersect the layers of pyroclastic deposits almost at a right angle without noticeable displacement of the nearby fragments. Also there is little evidence that magma has a mechanical impact on the host rocks. Many researchers believe that the rise of magma occurs under the rising pressure. Gudmundsson A. (Gudmundsson, 2002) believes that the excess pressure of magma in a dyke is not associated with fissures or fractures at their ends. Walker G.P.L. (1987) showed that the basaltic melt intrusion with the release of space in massive basalts is the result of melting.

The magma reservoirs formation at the bottom of the Earth's crust may occur due to the presence of a sequence of sheeted dikes that are relatively impenetrable to ascending ultramafic and basaltic melts. Probably this horizon has properties of a heat insulator which are constantly renewing. The resumption of these properties of sheeted dikes sequence is due to the nature of thermal energy. It has a tendency to self-isolation and preservation of heat in the magmatic cell. Therefore, it is assumed that the high-temperature ultramafic and basaltic magma may intrude into the horizon of the sheeted dikes following the heat transfer medium which has a large internal energy (transmagmatics fluid). A large portion of intruding melts remains in this horizon and they become more dense and heavy when there are heat losses. The lowering of magmatic structures into the mantle occurs (Peterson, Moore, 1987).

3.2.2. Magmatic heat-transfer agents

Korzhinsky D.S. (1952) proposed the hypothesis about flows of transmagmatic fluids (supercritical fluids) in magma. On his opinion, the mantle is the source of such fluids. It was assumed that these fluids formed granitic magma during K-Na metasomatic process which indicates that alkalis in the magma are mobile.

In the early 1900s, after the publication of the classification of ore deposits by Lindgren (1933), geologists believed that the epithermal vein systems were formed from emanations of deep magma chambers. Later, a concept about the important role of meteoric water became predominant. This concept was confirmed by the studies of hot springs and stable isotopes of active and fossil hydrothermal systems. At the Seminar on magmatic components in hydrothermal systems in Ebino and Kagoshima (Hedenquist, 1992), the consensus was reached that magmatic fluids were in chemical, isotopic and thermal equilibrium with melts. It is believed that at a depth of several kilometers water is the main component of these fluids. They may contain significant amounts of CO_2 and S (SO_2, H_2S), NaCl, KCl, $FeCl_x$, $CaCl_2$, HCl, HF and metals (Muffler et al., 1992). In our opinion, this conclusion is not convincing enough. The ratio of emitted water vapor and heat from the eruptive channels in which magmatic melts are in a stagnant mode is questionable (Fig. 6).

Figure 6: Active eruptive channel of Gorely volcano. Kamchatka. (http://www.photokamchatka.ru/photos/photo.php?ID=24908&sphrase_id=2835682)

The high flow rate of water vapor with high enthalpy indicates both the large inflow of water into the magmatic channel and the large flow of heat in this channel. Basaltic magma can not be the source of such amount of water. It is assumed that water comes in the channel from an external source. Basaltic magma of the Hawaiian volcanoes has low contents of water (Wright, Helz, 1987). The thermal energy of steam jet may be delivered only via magmatic channel. This requires a heat transfer medium with a large internal energy.

The observation of the initial stage of the eruptions of fissure volcanoes, in particular, in Kamchatka (the Great Fissure Tolbachinskii Eruption 1975-76, 1984) testifies that the formation of fissures through which high temperature fluid is discharged occurs before the outpouring of basaltic melt. The high temperature fluid warms up basalt rocks to melt. The process of melting is accompanied by release of volatile components. The chemical analysis of this volatile phase indicates that exothermic oxidation-reduction processes (like combustion) with the release of large amount of heat occur in magma. Large concentrations of alkali metals were found in the pneumatolytic mineralization products on modern volcanoes (Naboko, Glavatskih, 1985). Both alkali-metasomatism and alkaline magmatism play a leading role in the formation of porphyry deposits and hydrothermal ore deposits associated with intrusions. These deposits are formed by hydrothermal-magmatic systems (Pirajno, 2009).

Belousov V.I. (1978) has shown that alkali metals could be important agents in the transportation of thermal energy in magmatic melts and hydrothermal fluids. Sodium has a heat of fusion 26.8 kcal/kg and a heat of vaporization 1038.4 kcal/kg. Potassium has a heat of fusion 14.34 kcal/kg and a heat of vaporization 498.24 kcal/kg. Eutectic alloy with 78 wt. % of potassium and 22 wt. % of sodium has a heat of fusion of 19.2 kcal/kg and heat of vaporization (828 kcal/kg) (Chirkin, 1968). Thus, the enthalpy of the vapors of Na, K and eutectic alloy Na (78%) +K (22%) is more than 1000, 500, and 800 kcal/kg, respectively, with the temperature of melt 1000-1200ºC. In this regard, sodium and potassium can transport significant amounts of heat in the magmatic convective cell from the upper mantle to the Earth's surface at a significant rate caused by the large temperature gradient at its ends.

These components are carried out in the volatile phase with a large internal energy. Transferring the heat, a jet of volatile components keeps the high temperature of the silicate mass of magmatic melt. At this conditions, the volatile phase contains molecular gases, electrons and ions, including ions of alkali metals. Alkali metal is an easily ionized component that supplies electrons and ions. Molecules of alkali affect the energetic and kinetic characteristics of plasma. Thus, the phase of volatiles in magma may correspond to low-temperature plasma. Low-temperature plasma represents ionization of heavy particles, excited particles, adhesion of electrons, etc. (Klucharev et al., 2008). Some modern plasma technologies use pyrolysis gases. The composition of these gases is similar to the composition of volcanic gases. According to this technology, the pyrolysis process is carried out with a formation of hydrogen and carbon monoxide at temperatures ~2000°C and that provides high caloric content - up to Qi = 2 400 kcal/kg (10,0 MJ/kg). Vapors of alkali metals are ionized at a temperature of 2000ºC (Lunacharsky, Shipachev, http://www.autowelding.ru/blog/ kholodnaja_nizkotemperaturnaja_plazma/2011-08-02-100). According to the study of the physical chemistry of pyrometallurgical processes, these gases are in balance with a multi-component melt. During complicated processes of chain reactions they are being converted into water vapor, carbon dioxide and other gases (Esin, Geld, 1966). Alkali metals affect the chain reactions of gases. They lower the temperatures of gaseous elements ionization and increase the internal energy of volatile phase of magma. It is assumed that a significant portion of heat energy in magmatic processes can be transported by gaseous and easily movable components. In intrusive processes, these components spread in the host rocks (alkaline metasomatism) and give them the thermal energy. The gradual accumulation of thermal energy occurs. This energy heats pore and fissure water which leads to the welding of mineral particles and formation of welded tuffs and ignimbrites. In fiamme of ignimbrites the increased content of sodium and potassium can be observed. It is assumed that in this case the formation of melt in the form of selective meltings in metamorphic strata is possible (Belousov, 1978).

Volcanic gases ionization is confirmed by Leonov V. L. (1979) during the research of the Great Tolbachik Fissure Eruption in 1975-76. The Southern eruptive center of this eruption is characterized by a cyclical flow of basaltic magma. Leonov V. L. showed that the change in the flow rate of lava of the Southern eruptive center was similar to the changes of the geomagnetic index and relative numbers of sunspots. Belousov V. I., who consulted these studies, considers that such a relationship between magmatic and solar activity indicates an electrical conductivity of basaltic melts in which volatile components migrate in the condition of a low-temperature plasma. The perturbation of the Earth's magnetic field caused by the solar activity enhances the migration of electrons and ions, including those of alkali metals. In this regard, the heat flow in the magmatic channel increases and the temperature of magma rises. The rise of magma temperature increases the detachment, the rate of rise and expansion of the molecular gas phase. This process lowers the level of magma in the eruption channel by a gas lift and increases the flow rate of a lava flow.

4. THE MECHANISM OF HEAT TRANSFER IN HYDROTHERMAL-MAGMATIC SYSTEMS: A CONCEPTUAL MODEL

The magmatic-hydrothermal system in the regions of active volcanism consists of hydrothermal and magmatic convective cells. In a hydrothermal cell, thermal water is the main heat carrier. There are gases and cations (mainly of alkali metals) brought into water from the magmatic convective cell. It is possible that there is also a small proportion of primary magmatic water of the mantle basaltic melts. Since oxygen is the most widespread element, and hydrogen is its companion in the water molecule, the ratios of $^{18}O/^{16}O$ and D/H, where D is deuterium ($^{2}{}_{1}H$), the heavy isotope of hydrogen, can be powerful indicators or tracers of the sources of hydrothermal fluids. Isotopic changes in meteoric water depend on the latitude and absolute level of the values δD and $\delta^{18}O$ decreasing at large elevations and high latitudes. This is a result of the less evaporation and smaller fractionation of these isotopes vapor-fluid which facilitates the transition of the lighter isotope in the vapor phase, and the remaining fluid is enriched in heavy isotopes. Thus, boiling water is enriched in $\delta^{18}O$ and δD compared to steam.

It is assumed that magmatic water contains a larger proportion of heavy isotopes of these elements, compared to meteoric water. This is due to the fractionation of light isotopes at magmatic temperatures. Evaporation, condensation, melting, crystallization, adsorption and diffusion processes explain the mechanism of isotopic fractionation (Pirajno, 2009). However Taylor H.P. (1997) said that the isotopic range O and D within the magmatic box by no means signifies that natural water is of magmatic origin. The similarities of the D/H ratios in minerals of igneous and metamorphic rocks make it impossible to distinguish between magmatic and metamorphic water on the basis of δD values alone. It makes the use of this method of determining magmatic water in hydrothermal-magmatic systems questionable. If meteoric water interacts with magmatic melts, it may have isotopic values of the primary magmatic water. In this regard, the conclusion made at the Japanese-American Seminar in Ebino and Kagoshima (Hedenquist, 1992) about the important role of magmatic water in porphyry ore systems requires an additional analysis.

In a hydrothermal cell heat transfer mainly occurs as a result of free convection which is caused by the gradients in density and temperature of water. In the places where water temperature reaches the boiling point at the hydrostatic pressure, free convection is complicated by the forced convection. It is caused by a phase transition (vapor generation) and intensive release of non-condensable gases which form a gas-liquid stream with an effect of gas lift as a result of the upward flow of the gas phase. This process is known as hydrothermal (phreatic) explosion or hydrothermal-magmatic (phreato-magmatic) eruption. In the latter case, there is a fresh igneous rock in the composition of the eruptive products. This indicates that in the process of the hydrothermal explosion the intrusion of magmatic melt occurs which increases the flow of heat into the hydrothermal cell. This flow lowers the water level and forms a depression funnel in the hydrothermal cell (Fig. 7). A significant decrease in water level increases the heat loss of the magmatic convective cell. Water migrates into this funnel and the water level in a hydrothermal cell is restored. The temperature of the water decreases.

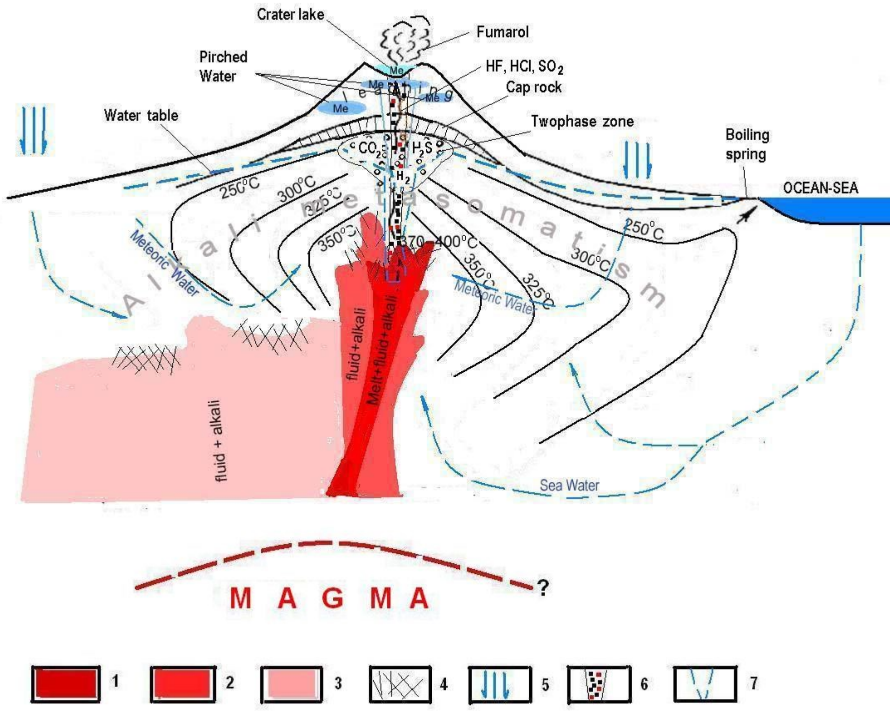

Figure 7: Schematic drawing showing the interaction of hydrothermal and magmatic cells during the hydrothermal-magmatic eruption. 1 - hot intrusion of alkaline granitoids; 2 – crystallizing alkaline granitoid melt; 3 – late injection of alkaline granite magma; 4 – stockworks: brine + dilute meteoric water + ore veins; 5 – meteoric water; 6 – diatreme associated with late injection of alkaline granite magma; 7 – the water level near the diatreme.

In the contact zone of water, hot rocks and magma, large gradients of temperature are formed. A dramatic cooling, decrease of the volume of rocks and formation of cracks occur. Water starts to boil, and the mineralization of hydrothermal increases until the brine is formed. Highly mineralized brines are formed probably from condensate water enriched in metals leached of the crater lakes and water heated by steam. Such brines can form a system of ore-bearing veins (stockwork). A similar process can be observed in the craters of some volcanoes (Fig. 8).

Figure 8: The surface of the lava flow is covered with numerous cracks, in which meteoric water is transformed into steam. Avachinsky volcano. The eruption of 1991. Kamchatka (Belousov.pro)

Lowering the temperature of the igneous body and hot host rocks, water gradually heats up. The heating rate depends on the quantity of water in the piezometrical depression funnel. Small water table above the magmatic body are apparently typical of the central volcanoes with frequent small explosions. The ash eruptions of Karymsky Volcano in Kamchatka are the example. The figure 9 shows the evolution of the eruptive volcano eruption similar to the eruption of a geyser.

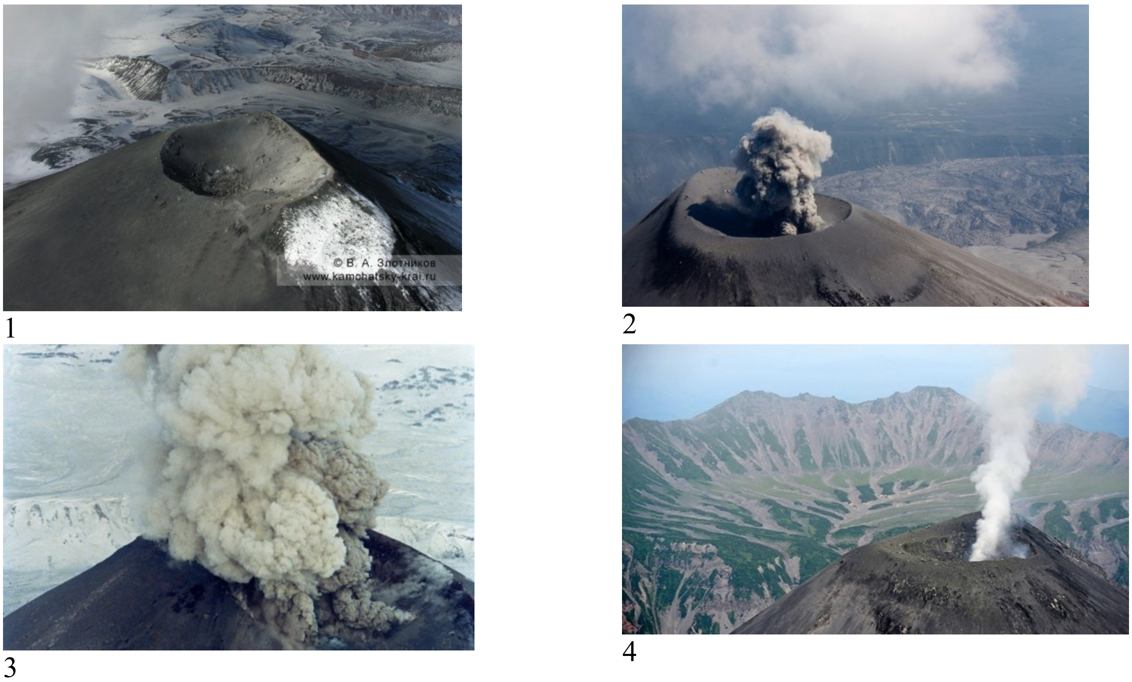

Figure 9: the stages of the magmatic-hydrothermal (phreato-magmatic) eruptions of Karymsky volcano, Kamchatka. 1 - heating water in the aquifer complex (perched), water discharge buried; 2 - start water boiling and the escape of steam; 3 - maximum boiling and eruption; 4 - evaporation (www. Kamchatski-krai.ru)

Thus, in the magmatic system a significant temperature gradient is created. The cooling of magma chambers in the crust and their turning into small intrusions stabilize silicate magma. The temperature gradient of the magmatic cell causes migration of volatile phases in it and also the migration of heat from the mantle to the Earth's surface. Interaction with hydrothermal cell appears in the heat transfer in the contact zone, as a result of molecular transfer and forced convection. It is caused by the gradient of alkali metals concentration between the melt and hot alkaline rocks. This process is supported by the studies of fluid inclusions in the rocks of the transition zone of hydrothermal and magmatic cells in the Kakkonda hydrothermal system in Japan (Sasaki et al., 1995).

At the Kakkonda geothermal field, fluid inclusions in quartz of granites had homogenization temperatures in the range from > 330°C with a salinity of < 20 wt. % (NaCl eq.) to 380-510°C with a salinity of 60-75 weight. % and the molar ratio Na/K in high-temperature and highly mineralized inclusions of 1.2-2.3. This ratio of Na/K is similar to that of hydrothermal solutions in equilibrium with granites, which are determined by the experiments (Sasaki et al., 1995). Inclusions with lower homogenization temperatures and lower mineralization are the analogues of hydrothermal formed as a result of the mixing of highly mineralized and weakly mineralized hydrothermal solutions. Hydrothermal solutions circulating in granites were gradually transformed from highly mineralized to weakly mineralized solutions. These data indicate that during the interaction of meteoric waters of the hydrothermal cell with the magmatic cell the formation of brines happened. They are by their thermo-physical properties close to a solid state and are not capable of free convection. This interaction leads to the transfer of alkali metals from magma to brines. Migration of alkalis and heat may be caused by the gradient of their concentration. Brines mix with weakly mineralized thermal water and heat it. This leads to the formation of a convective hydrothermal cell in which free convection dominates. Heat losses of the magmatic cell are compensated by the inflow of trans-magmatic fluids with alkali metals. They come in a magma chamber under central volcanoes by magmatic channels having the configuration of a thin plate. As the melt cools down, magmatic channels are transforming into dikes. These structures are characterized by a large cooling surface and small volume which results in a large specific heat loss.

These heat flows can be provided by heat carriers with a large internal energy (low temperature plasma) and by the mobilization of heat from a powerful source. Magmatic reservoirs of basaltic melts can play the role of such source. Mobile elements will be concentrated in the head of the magmatic channel. Here focuses the high-power thermal flow that melts the rocks and then magma penetrates them. Thus, the dikes are the primary structures, magmatic channels for the transportation of a large quantity of heat through the Earth's crust. Large heat losses lead to the rapid cooling, hardening and reduce of the permeability of magma, especially in the layer of sheeted dikes. This horizon is a good heat insulator. Below the horizon of sheeted dikes may occur the accumulation of heat, high-energy magma and volatile phase in which alkali metals are concentrated.

G. B. Flerov and others (2015) studied the magmatic system of the Tolbachik center on the Kamchatka Peninsula. They proposed a conceptual petrologic-geodynamic model for the origin of magma of this center. It confirms the above mentioned assumptions about the migration and accumulation of alkali metals in basaltic melts. According to this model, the reservoir of basaltic magma is located at the crust–mantle border. The intrusion of basaltic melts from the upper mantle was accompanied by the formations of magma chambers in the Earth's crust and fissure eruptions at the surface. Eruptions of basaltic melt stopped and trachybasaltic eruption of magma started from the same reservoir in which the alkaline melt intruded from below. It is assumed that there are two magmatic reservoirs at different depths which interact to form magma of intermediate composition.

According to our concept, the formation of trachybasaltic melt occurs in the same basalt reservoir, and this process is caused by the migration of trans-magmatic fluids containing alkali metals. Migration of these fluids is the result of heat loss, temperature reduction in the basalt reservoir and increase of the temperature gradient in the magmatic system. Accumulation of trans-magmatic fluids in the basalt reservoir to the critical limits is a crucial factor in subsequent eruptions of trachybasaltic melts.

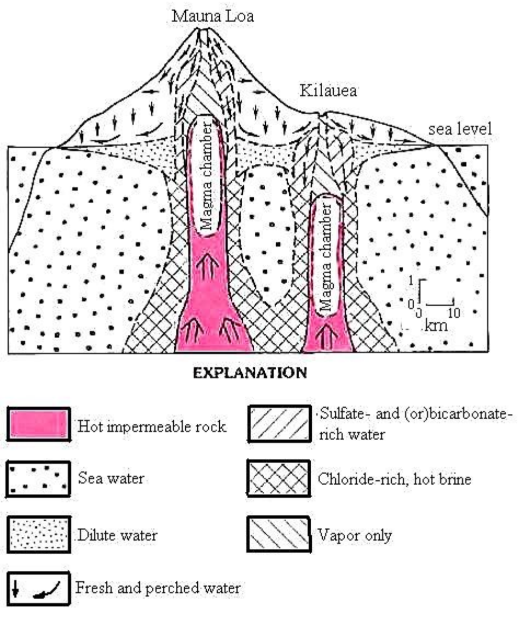

Figure 10: Schematic illustration showing the shallow magma chambers and associated hydrothermal system of volcanoes Mauna Loa and Kilauea, Hawaii (Fournier, 1987)

Decker R.W. (1987) noted that magma chambers under the Kilauea and Mauna Loa volcanoes were located at a depth of ~3 km from the respective peaks (Fig. 10). He concluded that "the continuing evolution of Hawaiian volcanoes, obviously, leads to a progressive melting up to the release space (stoping) and (or) pushing people around to the sides of the rocks that overlie a system of shallow reservoirs". Under the assumption that, if the depth of 3 km to the roof of a shallow magma reservoir is retained approximately since the beginning of the formation of volcanic edifices of the Hawaiian type to the formation of structures on the seabed during the growth of the island, generalizations can be made about the probable link with the hydrothermal system. Fournier R.O. (Fournier, 1987) suggests that this is due to the chemical transformation of marine pore water, thermal regime around magma chambers, interaction of the transforming water with rocks at high temperatures and increasing pressure of non-condensable gases.

According to our concept, migration of the magma chamber is closely connected with the migration of the hydrothermal convective cell localized in the upper part of the volcanic edifice. This process is determined by the continuity of the anomalous heat flow from the upper mantle to the Earth's surface, the increase in temperature gradient in the magmatic convective cell and by the change of a trans-magmatic heat-transfer agent in the transition zone from the magmatic convective cell to hydrothermal convection cell, where meteoric water is a dominant heat-transfer agent.

5. CONCLUSION

Heat flow of geothermal areas is 50 to 100 times bigger than the average heat flow of the Earth. In the hydrothermal-magmatic systems convective heat transfer dominates. In the upper part of the system, water and volcanic gases are heat-transfer agents. In the bottom part of the system silicate melts and high-energy phase of volatile components (trans-magmatics fluid) dominate as heat-transfer agents. The composition and thermodynamic condition of volatile components phase are determined by the composition and thermophysical properties of melts. In magmatic fluids the special role in the exchange of heat between hydrothermal and magmatic cells is played by alkali metals. The functioning of hydrothermal-magmatic convective systems is mainly due to the heat balance and temperature gradient which control the anomalous heat flow in the crust and upper mantle. The violation of the thermal balance in hydrothermal-magmatic systems is due to the change of their structure in the process of interaction between heat flow and surrounding rocks. This process associates with periodic eruptions of mobile heat transfer mediums (melts and volatile phases).

Thus, the formation of the geological structure of such systems is the result of a heat flow self-organization from the mantle to the Earth’s surface. The behavior of a heat flow is characterized by minimization of heat losses and accumulation of heat in some areas of the Earth's crust. Accumulation of heat in hydrothermal-magmatic systems is necessary to maintain their operation.

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