

Petrophysical Alteration of Volcanic Rocks in Hydrothermal Systems of the Kuril-Kamchatka Island Arc

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ABSTRACT

This report is based on complex petrophysical data obtained on a number of hydrothermal systems in the Kuril-Kamchatka island arc (Pauzhetskaya, Mutnovskaya, Koshelevskaya, Essovskaya, Northern-Paramushir, and Baranskogo). The mineral composition and porous structure of primary rocks are intensively altered by hydrothermal processes, resulting in changes of petrophysical properties. Petrophysical alteration of rocks gradually causes a transformation of hydrothermal system structure, which leads to changes in its hydrodynamic and temperature regimes.

The tendency of petrophysical alteration can be different. In some cases, rock "improvement" is observed, i.e. consolidation, hardening, a decrease of porosity and permeability, and removal of hygroscopy. In other cases, rock "deterioration" occurs, i.e. formation of secondary porosity and permeability; a decrease of density, strength and elastic modulus; and occurrence of hygroscopic moisture. The character of petrophysical alteration depends on a number of factors including peculiarities of primary rocks; temperature, pressure and composition of thermal fluids; duration of fluid-rock interaction; and fluid phase.

The properties of primary rocks control the speed, intensity and character of petrophysical alterations. Effusive and intrusive rocks are dense and low permeable with high strength and elastic modulus. They form water-confining horizons in the structure of geothermal fields, and rarely fracture-type reservoir. The speed of their alteration is low. Tuffs and tuffites differ significantly by lower physical and mechanical properties, higher magnitude of alteration and permeability character. They are the most common type of the host rocks of geothermal reservoirs.

The temperature and pressure in hydrothermal systems cardinaly influence on rocks properties. Deep, high-temperature fluids cause consolidation, hardening, a decrease of porosity and permeability, and removal of hygroscopic moisture. The influence of low-temperature subsurface fluids is more complicated and diverse. It can lead to either an increase or a decrease in petrophysical properties depending on what process prevails – rocks leaching, sedimentation of secondary minerals in pores and cracks, or replacement of primary minerals by secondary minerals. The chemical composition and pH of thermal fluids have a large influence on the alteration of rock properties for low-temperature fluids and are not important for high-temperature fluids.

Petrophysical alterations depend on the duration of hydrothermal processes. As a whole, hydrothermal systems are characterized by heterogeneity and selectivity of

processing, resulting in the petrophysical heterogeneity of all structures. However, petrophysically homogeneous zones are gradually formed by contact with thermal waters over long periods, causing the systems to become more stable.

1. INTRODUCTION

Geothermal energy is a renewable, relatively cheap and environmentally friendly. Geothermal potential is generally high in the regions of active volcanism and high heat-flow. In Russia, the richest geothermal heat reserves are located in the Kuril-Kamchatka island arc. Tens of low- and high-temperature hydrothermal systems are located in this region. Hydrothermal systems represent both scientific and practical interest. Scientific interests concern the formation, evolution, structure, ore formation, and localization of hydrothermal systems. Of practical interest is the exploitation of thermal water and energy as well as mineral extractions.

Characteristic features of geothermal reservoirs such as their capacity and longevity are mainly controlled by the composition, pore-space structure and petrophysical properties of the host rocks. Petrophysical properties are physical and mechanical characteristics of rocks, including: density, porosity, permeability, hygroscopic moisture, water absorption, sonic velocity, elastic modulus, strength, and magnetic, electric and thermal characteristics. These properties are determined in laboratories.

There is much to learn from petrophysics. It is most important to know the collective properties of host rocks: porosity controls reservoir capacity, and permeability characterizes water transport through the stratum. Thermal properties (thermal conductivity and thermal capacity) are also important as they control heat transport in the reservoir. Density, strength and elastic properties determine the state of stress in hydrothermal systems and the fracturing and formation of secondary permeability. Petrophysical properties are necessary as input data for numerical modeling of geothermal processes and are useful information for geophysical log interpretation. Knowledge of mechanical properties is necessary during drilling.

Thermal fluids can change the composition and properties of host rocks. The tendency of petrophysical alteration can be different. The classical example of cardinal petrophysical alteration is the transformation of hard basalts into plastic clays. The opposite example is the transformation of only slightly consolidated porous tuffs into hard, dense secondary quartzite or high-temperature propylites. Petrophysical alteration gradually causes a transformation of hydrothermal system structure as a whole and leads to a changes in hydrodynamic and temperature regimes. Thus, knowledge of the petrophysical properties in hydrothermal systems and the investigation of alteration dynamics are of great importance.

2. GEOLOGICAL SETTING AND GEOTHERMAL CONDITIONS

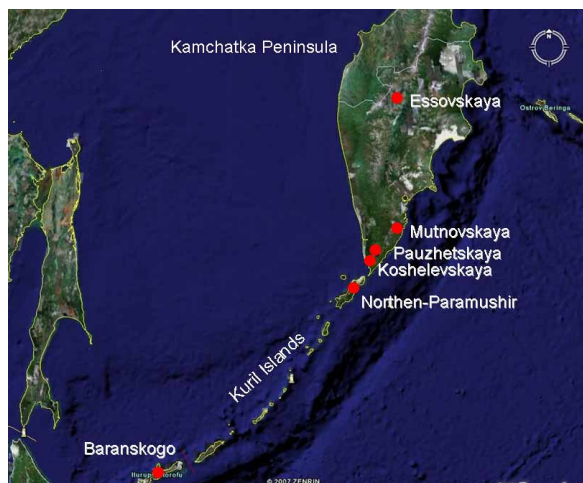


Figure 1. Location of studied hydrothermal systems

The Kuril-Kamchatka region is the volcanic island arc located in the northeastern segment of the circum-Pacific belt. Geothermal resources in the Kuril-Kamchatka arc are closely associated with active volcanism and its tectonic position above a subduction zone. Generally, the geological, hydrogeological and geothermal conditions of the Kuril-Kamchatka arc are favorable for the formation of hydrothermal systems, especially in the Central and Eastern volcanic belts and on the Kurils. All types of geothermal manifestations are present in the Kuril-Kamchatka arc: fumaroles, steams jets, steaming ground with boiling and seething pools, sulfur-mud pools, geysers, springs (boiling, hot and warm), and thermal lakes and creeks. Most geothermal areas are associated with Pleistocene to Holocene calc-alkaline volcanoes. The host rocks of hydrothermal systems are volcanic or volcanoclastic types of Neogene-Quaternary age. The locations and short characterizations of the studied hydrothermal systems are given in Figure 1.

Essovskaya hydrothermal system is located on the Sredinny Ridge. This geological section is composed of Neogene-Pleistocene tuffs and lavas. There are a lot of hot springs in this region with temperatures up to 95 °C and mineralization up to 3 g/l (Pilipenko, 1998). The system has not been well studied thus far. The petrophysical properties of 23 samples from outcrops related to this system were investigated.

Pauzhetskaya hydrothermal system is located in Southern Kamchatka on the slope of Kambalny Ridge inside a volcano-tectonic depression. It is well-studied system. The first geothermal power station with an installed capacity of 5 MWe has been operating there since 1967. The hydrothermal system is composed of Neogene-Pleistocene tuffs alternating with lava flows and dykes. The system is in a regressive stage of development. The rocks are intensively altered by thermal fluids (up to 180-200 °C), resulting in mineralogical and petrophysical zoning. The following zones are distinguished in geological section of hydrothermal system (down to 600 m): argillic alteration (smectite, high-silica zeolites, opal), zeolitic (laumontite and corrensite), and propylites (chlorite, calcite, sericite, albite). “Flash” zones composed of quartz and adularia have developed in some faults. The main reservoir is composed of highly permeable medium-course grained tuffs and is associated to the zeolitic zone. The cap rocks are composed of fine-grained argillized tuffs. We investigated the

properties of 202 samples from 6 boreholes within geothermal field and 21 samples from outcrops out of hydrothermal influence (Ladygin et al, 2000).

Mutnovskaya hydrothermal system is one of the most prospective and best studied geothermal regions. It is located approximately 70-80 km south of Petropavlovsk-Kamchatsky. There are two GeoPP power stations under operation with installed capacities 12 and 50 MWe. It is a high-temperature system with temperatures up to 280°C and is in an extreme stage of evolution. It is assumed the main production zone correlates with a fault (Kiryukhin et al., 2004). Complex compounds of Oligocene-Quaternary rocks compose the Mutnovsky region including volcano-sedimentary and volcanoclastic rocks, lavas, extrusive rocks and ignimbrites. The following alteration zones occur down to depths of 1000 m: acid sulfate leaching (opal, cristobalite, tridymite, alunite, kaolinite), argillic (smectite, high-silica zeolites), low-temperature propylites (illite, calcite, chlorite), quartz-wairakite-prehnite and middle-temperature propylites. The properties of 75 samples from 4 boreholes and 45 samples from outcrops were investigated.

Koshelevskaya hydrothermal system occupies the most southern position on Kamchatka peninsula and is located on the slope of a volcano of the same name. It is a high-temperature system and is under investigation at present. Temperatures reach 260 °C at the depths of 1100 m (Belousov and Sugrobov, 1976). Host rocks are volcanic and volcanoclastic types of Neogene-Quaternary age. The properties of 17 samples from outcrops were investigated.

Northern-Paramushirskaya hydrothermal system is situated on the slope of the active volcano Ebeko on Paramushir Island (the Northern Kurils). Geological section down to the depth 2500 m consists of Miocene-Pleistocene tuffs, volcano-sedimentary rocks and andesite and andesite-basalt lavas. The hydrothermal system has the following alteration zones: low-temperature opalites, quartz-adularia-sericite, and middle-temperature propylites. Temperatures reaches 180-250°C at depths of 1.5-2.5 km. The system is in a progressive stage of evolution (Rychagov, 2005). The properties of 35 samples from 5 boreholes and 20 samples from outcrops were investigated.

The Baranskogo hydrothermal system is located on the slope of the volcano Baranskogo in the middle part of Iturup Island (in the Southern Kurils). It is a high-temperature hydrothermal system in a progressive stage of evolution with temperatures above 300°C at a depth of 1.2 km (Rychagov et al., 2005). Two GeoPP “Tuman” are in operation there with a total installed capacity of 3.6 MWe. The host rocks are Pliocene-Quaternary volcanoclastic rocks interbedded with lavas and dykes. A shallow intrusion is assumed to be the heat source of the hydrothermal system. The entire rock section is impacted and altered by thermal fluids. The following alteration zones are distinguished (down to 1.2 km below the surface): acid sulfate leaching (opal, tridymite, cristobalite, ferric oxide, kaolinite, alunite); argillic 1 (smectite, high-silica zeolites, opal); argillic 2 (corrensite, calcite); zeolitic; middle-temperature propylitic (chlorite, quartz, wairakite, albite, epidote, sericite); and secondary quartzites. The regular zoning is disturbed by “flash” zones with quartz, adularia, and wairakite. The properties of 253 samples from 11 boreholes were investigated (Ladygin et al., 2000).

3. ANALYTICAL METHODS

3.1 Petrophysical Measurements

Petrophysical analysis included the following determinations: bulk density (ρ), specific density (ρ_s), total porosity (P), water absorption (W), effective porosity by water (P_w), hygroscopic moisture (W_g), velocity of longitudinal waves in dry (V_p) and water-saturated (V_{pw}) environments, elastic modulus, uniaxial strength (compression) (σ_c), and magnetic susceptibility (χ). Standard methods and plug ($H \gg D = 2$ cm) or cubic samples were used for the majority of petrophysical measurements (Trophimov and Korolev, 1993).

Bulk density (ρ) is the mass per unit volume. It depends on the mineral density, moisture, and porosity. Bulk density was determined by standard measurements of the geometry and weight of the samples.

Specific density (ρ_s) depends on mineral composition only. It was measured for rock powder on a PELA apparatus, which uses the law of Boil-Moriotte (pressure*volume=const in isothermal environment). Accuracy was within 0.02 g/cm³.

Then, *total porosity* of rock was calculated according to Equation 1:

$$P = \{(\rho_s - \rho) / \rho_s\} 100 \quad (1)$$

where ρ , and ρ_s are bulk density and specific density, respectively

Water absorption (W) was determined by weighing the samples after a 7 day saturation period, and using these values in Equation 2:

$$W = \{(m_2 - m_1) / m_1\} 100 \quad (2)$$

where m_1 and m_2 are the mass of dry sample and the mass of the water-saturated sample, respectively.

The *effective (connected) porosity by water* was calculated according to Equation 3:

$$P_w = W \rho / \rho_w \quad (3)$$

where ρ_w is density of water.

Hygroscopic moisture (W_g) characterizes the content of bound water due to adsorption from the air. Hygroscopic moisture was determined after drying the rock powder in a thermal oven ($T=107^\circ\text{C}$, 24 hours) and was calculated using Equation 4:

$$W_g = \{(m_1 - m_2) / m_2\} 100 \quad (4)$$

where m_1 and m_2 are the masses of air-dry and absolutely dry powder, respectively.

Velocity of longitudinal waves (V_p) were measured using the ultrasonic method (DUK-6B – frequency 700 kHz and US-13 I – frequency 1 MHz) in air-dry and water-saturated environments. The coefficient Q_{vp} was calculated based on the difference of those values, as seen in Equation 5:

$$Q_{vp} = \{(V_{pw} - V_p) / V_p\} 100 \quad (5)$$

where V_p and V_{pw} are the velocities of longitudinal waves for dry samples and water-saturated samples, respectively.

The elastic modulus was calculated through sonic velocity and density according to Equation 6:

$$E = V_p^2 \rho \frac{(1 + \mu)(1 - 2\mu)}{1 - \mu} \quad (6)$$

where V_p , ρ , and μ are the velocity of longitudinal waves, density, and Poisson's Ratio, respectively.

Poisson's Ratio is calculated according to Equation 7:

$$\mu = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)} \quad (7)$$

where V_p and V_s are the velocities of longitudinal and transversal waves, respectively.

The *uniaxial strength* (compression) was determined using a hydraulic press ZDM-10/91 for plug and cubic samples. The uniaxial strength was calculated according to Equation 8:

$$\sigma_c = P / S \quad (8)$$

where P is a peak load which breaks sample; S is a square of sample side.

Measurements of uniaxial strength were made for dry and water-saturated samples.

Magnetic properties of rocks were characterized by magnetic susceptibility and determined by the Magnetic Susceptibility Meter (Kappameter KT-5).

3.2. Petrography and Geochemistry

Petrophysical properties were analyzed along with the composition and structure of the rocks. All samples were described macroscopically, then studied in thin sections with an "Olympus" BX-41 transmitted light polarizing microscope and polished section with reflected light. Mineral composition was identified using a DRON-3 diffractometer. The total spectrum was obtained in a θ range of $0-60^\circ$. In order to determine clay minerals types, measurements were performed on glycolated powder samples after heating them to 500°C (θ range of $2-30^\circ$). Electron microscopy with microprobe analysis was performed on some of the samples (Camebax SX-50; LEO 1450VP with microprobe INCA 300).

4. THE MAIN FACTORS CONTROLLING PETROPHYSICAL ALTERATION IN HYDROTHERMAL SYSTEMS

The character of petrophysical alteration depends on a number of factors including peculiarities of primary rocks; temperature, pressure and composition of thermal fluids; duration of fluid-rock interaction; and fluid phase. The contribution of each factor to changes in the properties of volcanic rocks was considered and analyzed in detail.

4.1. Primary Rocks

The properties of primary rocks control the speed, intensity and character of petrophysical alterations. Factors favorable for alteration are high porosity and permeability, microcracks, clastic structure with weak cementation, high content of volcanic glass, and basaltic composition. On the other hand, primary rocks with low porosity and permeability, massive crystalline structures, and silicic composition are resistant to hydrothermal and petrophysical alterations.

Since the Kuril-Kamchatka region is a volcanic island arc, host rocks in hydrothermal systems there are mainly of volcanic or volcanoclastic type and Neogene-Quaternary age. The significant differences between the petrophysical properties of lavas and intrusive rocks from one hand and tuffs and tuffites from another are shown in Figures 2 and 3. Only fresh or slightly altered types were included in this comparison.

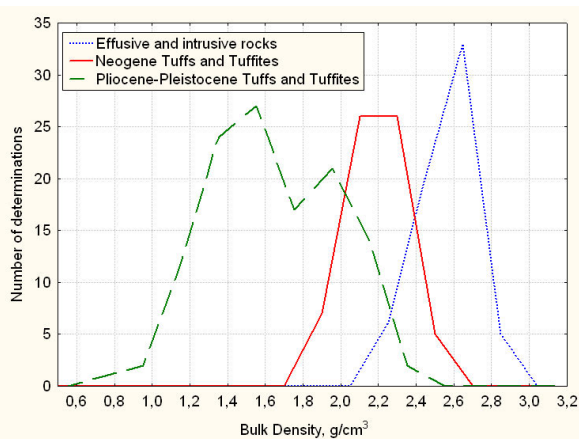


Figure 2. Bulk density histogram comparing lavas and tuffs.

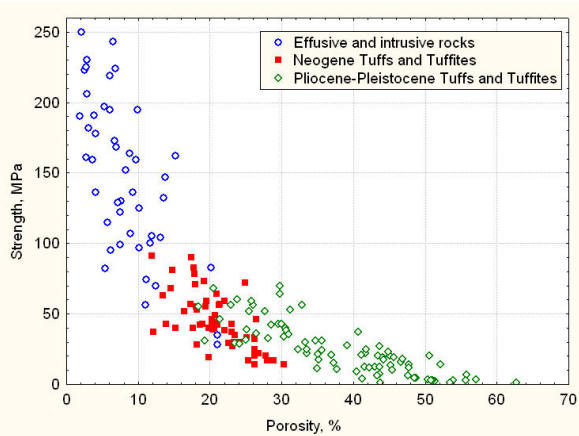


Figure 3. Variation of strength with porosity of both lavas and tuffs.

Lavas and intrusive rocks (andesites, basalts, diorites, dolerites) are characterized by strong crystallization contact between crystals, which are formed during lava cooling. So the rocks are dense ($\rho=2.3-2.8 \text{ g/cm}^3$) with low permeability and high strength ($\sigma_c=70-250 \text{ MPa}$), sonic velocity ($V_p>4 \text{ km/sec}$) and elastic modulus ($E=30-50 \text{ GPa}$). Due to low permeability, the speed of their hydrothermal alteration is low. Generally, they form impermeable horizons around hydrothermal systems, but in some cases, they form fracture-type reservoirs. The origin of fracturing can be primary or secondary. Primary fractures form due to thermal stress that develops during lava or intrusion cooling. However, secondary fracturing of tectonic nature contributes more to reservoir permeability. Tectonic fracturing is rather intensive, as exhibited in the investigation of the tectonically active area in this region.

Tuffs and tuffites have cementation contacts between grains that are formed during the lithification of loose pyroclastic deposits. They are characterized by low physical and mechanical properties and high porosity and permeability.

Due to high porosity and permeability, they are exposed to thermal fluids to a sufficient degree to be altered intensively. It was noted that Neogene rocks are more lithified and characterized by higher values of properties (mean values: $\rho=2.2 \text{ g/cm}^3$; $P=20\%$; $V_p=2.4 \text{ km/sec}$, $\sigma_c=45 \text{ MPa}$) in comparison with Pleistocene rocks (mean values: $\rho=1.6 \text{ g/cm}^3$; $P=38\%$; $V_p=2.15 \text{ km/sec}$, $\sigma_c=23 \text{ MPa}$). Tuffs and tuffites are the most common host rocks of hydrothermal systems in the Kuril-Kamchatka arc. Typically, they form porous or fracture-porous aquifers, but in some cases, they form water confining layers. The well-studied example is Pautzhetskaya hydrothermal system. The main reservoir is composed of highly porous ($P=30-40\%$) and permeable medium-grained tuffs. The caprock is composed of fine-grained argillized tuffs. They are highly porous ($P=30-50\%$), but due to small pore size, the permeability is low. Ultra-pores are filled by bound water which reacts with rock but is not filtered through the stratum.

4.2. PT-conditions in a system

The temperature and pressure in hydrothermal systems cardinaly influence changes in rocks properties. The difference between low- and high-temperature altered tuffs is illustrated in Figure 4. The density and strength of high-temperature tuffs exceed 2.3 g/cm^3 and 70 MPa , respectively. Sonic velocity is above 4 km/sec , and porosity is less than 15% . For tuffs altered by the action of low-temperature fluids, strength doesn't exceed 50 MPa , sonic velocity is less than 4 km/sec , density varies in a range $1-2 \text{ g/cm}^3$, and porosity is above 20% . Also, low-temperature rocks are basically hygroscopic, with bound water content of up to 5% . High-temperature rocks don't contain hygroscopic moisture.

Deep, high-temperature fluids ($>200^\circ\text{C}$) cause the following petrophysical alterations: consolidation, hardening, a decrease of porosity and permeability, and removal of a hygroscopic moisture. This petrophysical tendency was observed independently of fluid composition. This is the result of the development of secondary minerals (chlorite, epidote, zeolites, quartz, sericite, albite, adularia, prehnite, and calcite), which fill pores and cracks and substitute matrix and phenocrysts. The greatest changes in properties are caused by minerals filling intercrystal and intergranular micropores. The contacts between grains become stronger and denser, reinforcing the cementation of the rock. Intergranular pores are almost completely filled, reducing the total porosity and permeability.

The magnitude of alteration can be so high that the rocks lose their primary features. In this case, the initial differences in properties between tuffs and effusive rocks disappear.

Petrophysical alterations caused by low-temperature subsurface fluids ($T<150^\circ\text{C}$) are more complicated and diverse. Depending on what process prevails (rocks leaching, sedimentation of secondary minerals in pores and cracks, or replacement of primary minerals by secondary minerals), both increases and decreases in petrophysical properties can occur. The leaching of rocks by acid fluids raises porosity and lowers density, ultrasonic velocity, and strength. Sedimentation in pores leads to opposite property changes.

Property changes also depend on secondary minerals including the most extended clays (kaolinite or smectite depending on pH), alunite, opal, tridymite, cristobalite, and high-silica zeolites.

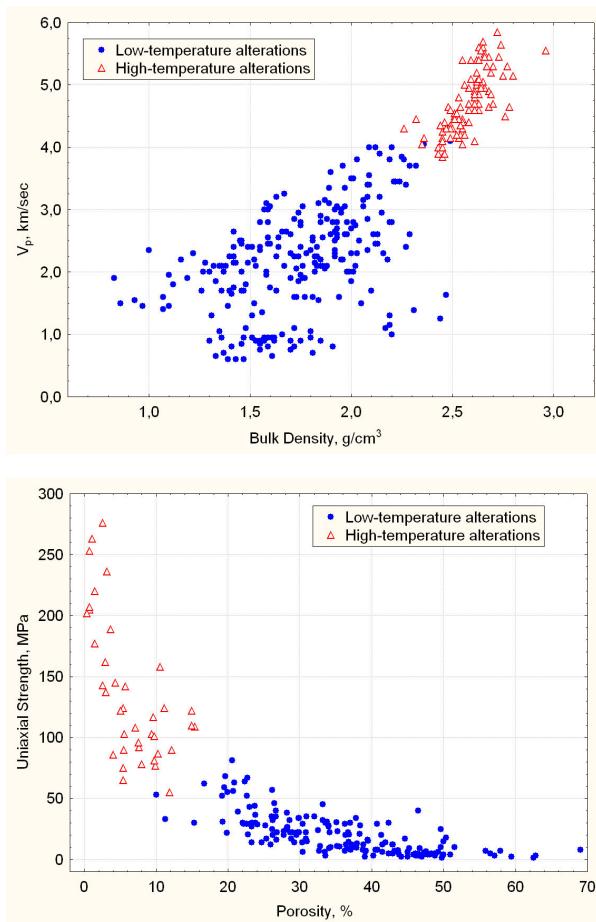


Figure 4. Comparison of low- and high-temperature altered tuffs. Upper figure - sonic velocity vs. bulk density. Lower figure – uniaxial strength vs. porosity

4.3. Chemical Composition of Thermal Fluids

Various mineral associations result from contact with thermal waters of varying chemical composition and acidity-alkalinity.

In particular, opalites are formed by sulphur acid leaching caused by sulphatic waters having pH 2-3. Siliceous minerals formed in this way (opal, chalcedony, quartz, tridymite, cristobalite) provide rigid structure to the rocks and cause an increase in the mechanical properties of rocks (σ_c =30-40 MPa; V_p ~3.0 km/sec), despite high porosity (30-35%) and low density (1.5-1.7 g/cm³). Hygroscopic moisture is about 1%. In some cases in geothermal fields lavas and tuffs transform to white light porous rocks composing of cristobalite that is confirm by X-Ray analysis. Cristobalite develops as films on the surface of grains. It consists of the nanocrystals as shown in Figure 5. Gradually cristobalite completely substitutes volcanic rock.

An increase in pH to 4-5 usually leads to the formation of alunite and kaolinite (Figure 6), which results in a decrease of mechanical properties of rocks (σ_c ~10 MPa; V_p ~1.5-2.0 km/sec), formation of hygroscopic moisture (1-5%), and reduction of permeability.

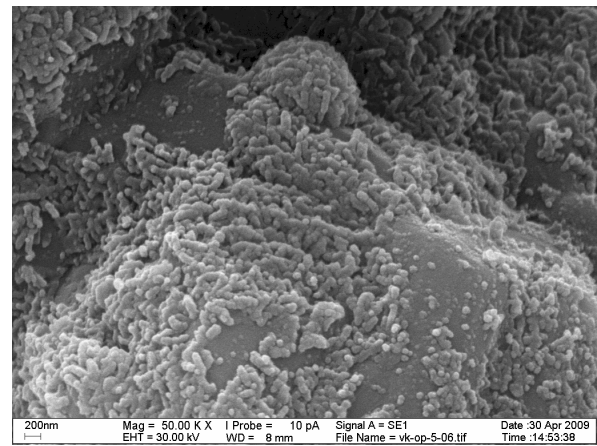


Figure 5. SEM image of andesite from Koshelevsky geothermal field replaced by cristobalite

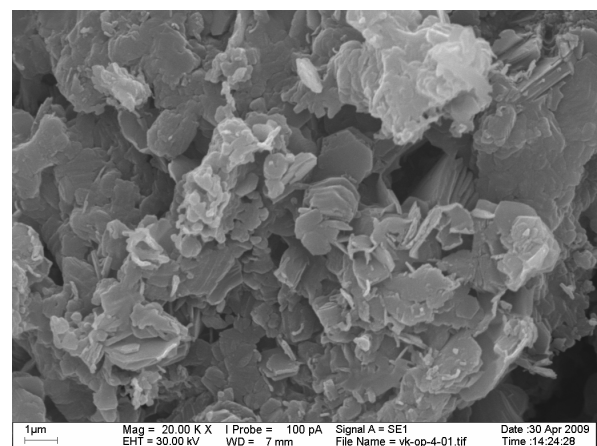


Figure 6. SEM image of andesite from Koshelevsky geothermal field replaced by hexagonal crystals of kaolinite

Under the influence of carbonic fluids with pH 5-6, smectites are formed. Smectites replace primary minerals, causing an appreciable decrease in mechanical properties (σ_c ~10-20 MPa; V_p ~2.0 km/sec) and an increase in hygroscopy (W_g =2-6%). Argillized rocks are unstable when saturated with water due to soaking and swelling. Strength decreases by a factor of two after saturation with water. Smectites also significantly reduce rock permeability in spite of high porosity (35-50%). They are characterized by ultra-small pores which are filled by bound water, which reacts with the rock but is not filtered through the stratum. The cellular microstructure of smectite is shown in Figure 7. Smectite “cells” have a size of about 5-7 microns. Smectite swells when saturated with fluid and fills intergranular pores and fractures, forming impermeable horizons. These argillized horizons are the impermeable caprock of the hydrothermal system (Frolova et al., 2006).

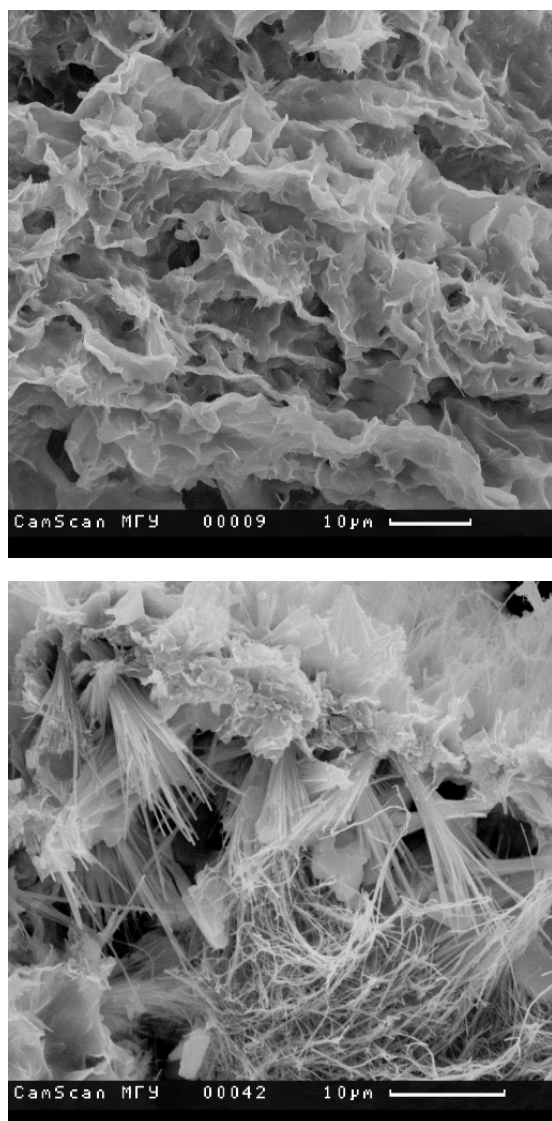


Figure 7. SEM images of argillic tuffs of Pauzhetskaya system: upper figure – cellular microstructure of smectite; lower figure – fibrous high-silica zeolites and smectite

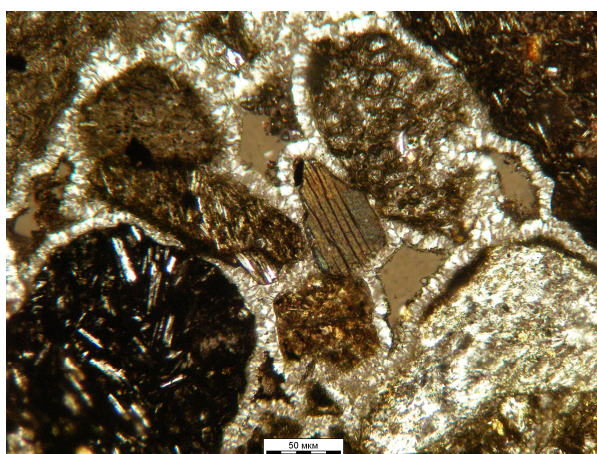
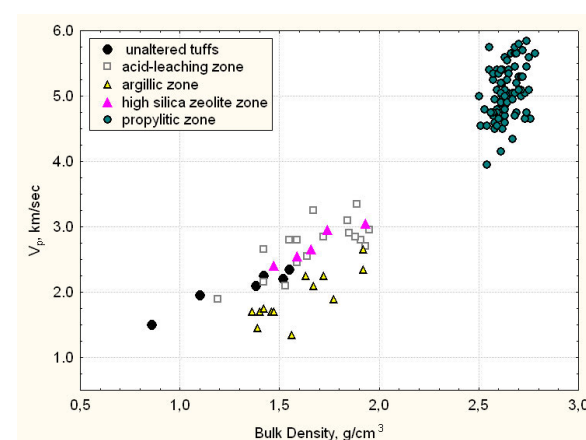
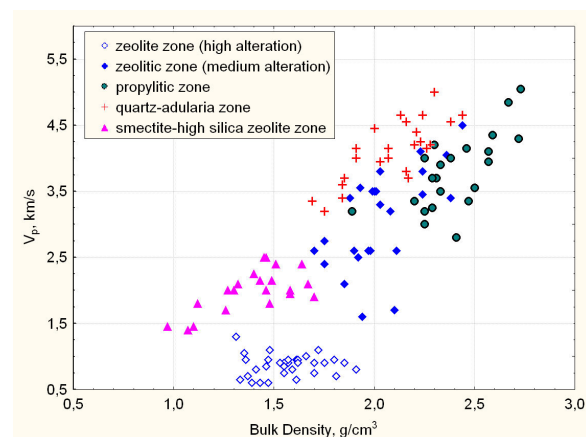


Figure 8. Thin section image: film-like zeolitic cement in tuffs of Mutnovskaya system

An increase of fluid pH to subalkaline conditions causes the formation of high-silica zeolites in association with smectites, as shown in Figure 7. High-silica zeolites form film-like cement with empty intergranular pores, as shown in Figure 8. These rocks have high porosities and low densities. Zeolitic rocks can be permeable, but their association with smectite reduces permeability.

4.4. Duration of Fluid-Rock Interaction

We compared three hydrothermal systems: Pauzhetskaya (the oldest, which is presently in a regressive stage), Mutnovskaya (in an extreme stage), and Baranskogo (the youngest, which is in a progressive stage) (Rychagov, 2005). The variation of sonic velocity with density is shown for each system in Figure 7, illustrating the difference in properties. Hydrothermal zones in the Pauzhetskaya system are intensively processed and therefore homogeneous. Each zone is segregated in the figure with almost no overlap. Different parent rocks in this system have been altered by thermal fluids to form homogeneous horizons, meaning the system has reached a sort of stability in petrophysical alteration. The case is similar for the Mutnovskaya system. However, the zones in the Baranskogo system (especially low-temperature) are heterogeneous and characterized by a wide dispersion of properties, as can be observed in the intersecting zones in the figure. This is due to the variation of the magnitude of alteration within each zone, where both fresh rocks and intensively altered types can be found, meaning that alteration is incomplete.



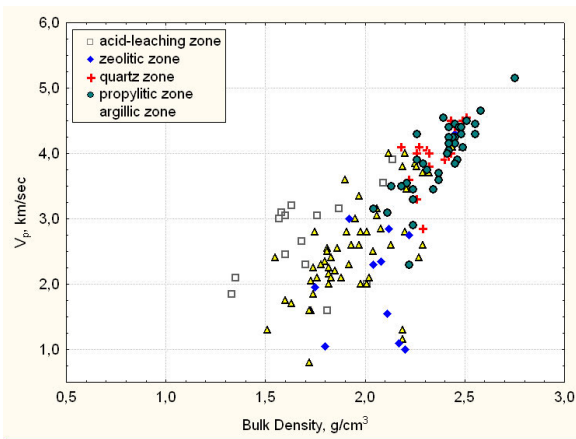


Figure 9. Variation of ultrasonic velocity with density for host rocks of hydrothermal systems: upper figure – Paughetskaya, middle figure – Mutnovskaya, lower figure – Baranskogo

5. CONCLUSION

Complex petrophysical analysis performed on a number of hydrothermal systems in the Kuril-Kamchatka island arc (Pauzhetskaya, Mutnovskaya, Koshelevskaya, Essovskaya, Northern-Paramushir, and Baranskogo) led to the following conclusions:

1. Thermal waters lead to appreciable petrophysical alteration of host rocks that in turn changes the structures of hydrothermal systems, as reflected by hydrochemical and thermodynamic conditions.
2. The tendency of petrophysical alteration depends on a number of factors including peculiarities of primary rocks; temperature, pressure and composition of thermal fluids; duration of fluid-rock interaction, and fluid phase.
3. Effusive and intrusive rocks from one site and tuffs and tuffites from another differ significantly in their properties and type of permeability. The former are characterized by higher density, strength, and elastic properties and lower porosity and permeability.
4. Deep, high-temperature fluids cause the following petrophysical alterations – consolidation, hardening, a decrease of porosity and permeability, and removal of hygroscopic moisture. The influence of low-temperature subsurface fluids is more complicated and diverse. It can lead to either an increase or a decrease in petrophysical properties depending on what process prevails – rocks leaching, sedimentation of secondary minerals in pores and cracks, or replacement of primary minerals by secondary minerals.
5. The chemical composition and pH of thermal fluids have a large influence on the alteration of rock properties for low-temperature fluids and are not important for high-temperature fluids.
6. Petrophysical alterations depend on the duration of hydrothermal processes. As a whole, hydrothermal systems are characterized by heterogeneity and selectivity of processing, resulting in the petrophysical heterogeneity of all structures. However, petrophysically homogeneous zones are gradually formed by contact with thermal waters over long periods, causing the systems to become more stable.

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