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Patterns in the Transformation of the Composition and Properties of Volcanogenic Rocks in Hydrothermal–Magmatic Systems of the Kuril–Kamchatka Island Arc

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Abstract—Hydrothermal–magmatic systems of the Kuril–Kamchatka island arc were formed in Neogene-Quaternary volcanic rocks. Acting on host rocks, thermal waters induced their alteration and transformation into hydrothermal–metasomatic rocks, such as propylites, secondary quartzites, zeolitic rocks, argillic rocks, opalites, quartz-adularia metasomatites, etc. The dynamics of changes in rock properties during the hydrothermal process depends on a number of factors, including the features of primary rocks, temperature, pressure and composition of thermal fluids, fluid phase, fluid pH, and duration of fluid–rock interaction. Deep high-temperature fluids cause consolidation and hardening of the rocks, an increase in deformational properties, and a decrease in porosity and permeability, regardless of fluid composition. The chemical composition and acidity–alkalinity of thermal fluids have a significant influence on the alteration of rock properties during low-temperature hydrothermal processes.

Keywords: volcanic rocks, hydrothermal alterations, physical and physico-mechanical properties, geothermal fields, hydrothermal–magmatic systems, Kuril–Kamchatka island arc.

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INTRODUCTION

The investigation of hydrothermal–magmatic systems (HMSs) and development of geothermal fields (GTFs) confined to them is ongoing in many countries. Many questions emerge, which include both application (problems of installation of electrical and heating systems) and research questions associated with studying the conditions of formation, evolution, HMS structure, dynamics, and mechanisms of geothermal processes, as well as ore and mineral formation.

The most intensive research is carried out in the United States, Iceland, Japan, Italy, New Zealand, Indonesia, China, Philippines, and a number of other countries (Bertani, 2010). In Russia, HMSs and proven geothermal fields are mostly located within the Kuril–Kamchatka region.

When studying these geological objects, one of the most important tasks is to study the host rocks. By acting on host rocks, thermal waters induce significant alteration and transformation of their mineral composition and the structure of the porous space, which results in alteration of the physical and mechanical properties of the rocks. The spectrum of thermodynamic and physical and chemical conditions under which the transformation occurs is extremely wide, resulting in a variety of newly formed rocks. Thus, volcanogenic rocks are transformed into completely new hydrothermal–metasomatic rocks, such as secondary quartzites, various propylites, zeolitic rocks, argillic rocks, opalites, quartz-adularia metasomatites, etc. Moreover, the alteration of properties may be different depending on different factors. In some cases, the improvement of the properties of the rock (i.e., consolidation, hardening, or a decrease in porosity and permeability) occurs; whereas in the opposite case, decompaction, weakening, the emergence of secondary porosity and permeability, and an increase in moisture capacity are observed (Frolova et al., 2011). In turn, the transformation of rocks results in the alteration of the structure of permeability of host rocks, elasto-plastic state of the rocks, and stress condition of masses, which may lead to the alteration of the hydrochemical, hydrodynamic, and temperature regimens of the system.

The studies performed by Soviet and Russian researchers (D.S. Korzhinskii, V.A. Zharikov, N.I. Nakovnik, A.A. Marakushev, S.I. Naboko, B.I. Omel'yanenko, V.L. Rusinov, V.A. Eroshchev-Shak, G.A. Karpov, S.F. Glavatskikh, A.D. Korobov, etc.), as well as those by D. White, A. Steiner, A. Ellis, D. Coombs, H. Kristmannsdottir, A. Reyes, J.W. Lawless, etc.

from Russia's abroad, contributed to the accumulation of vast data on the features of metasomatic and, particularly, the hydrothermal alteration of rocks. However, despite the variety of geochemical, mineralogical, and petrographic data on hydrothermally altered rocks, very sparse data on their physico-mechanical properties have been obtained. Research on the petrophysical characteristics of HMS rocks and design of the petrophysical database are carried out by the scientists of the Geological Survey of Iceland (Sigurdsson et al., 2000). Let us note the experiments of German researchers from the GeoForschungsZentrum Research Geocenter (Potsdam, Germany), who use a special apparatus to simulate conditions that correspond to the natural geothermal system and perform observations of alteration of petrophysical properties of rocks (Milsch et al., 2010). The alteration of physico-mechanical properties of rocks depending on the character and type of hydrothermal–metasomatic processes in the ancient endogenous fields of the Urals and Central Siberia is studied by the scientists of the Ural State Academy of Mining and Geology (Gryaznov, 2003).

Over many years, the authors have carried out investigations on the GTFs of the Kuril–Kamchatka region, which comprises complex studying the physical and mechanical characteristics of the host rocks and the dynamics of their alteration under action of thermal waters (Frolova et al., 1999; Frolova and Ladygin, 2008, 2010; Ladygin, Frolova, and Rychagov, 2000; Frolova, Ladygin, and Rychagov, 2001, 2010; Struktura ..., 1993). The summarization and analysis of the data obtained on Pauzhetskaya, Mutnovskaya, Koshelevskaya, Essovskaya, Northern-Paramushirskaya, and the Baranskogo GTFs enabled us to reveal the major patterns in the alteration of rock properties during hydrothermal processes and show the major factors that control these alterations. The data are of interest due to the development of geothermal power engineering in the Kuril–Kamchatka region.

Geological and geothermal conditions. The Kuril–Kamchatka region is located within the volcanic island arc of the same name in the northwestern segment of the Pacific Ring of Fire. Great reserves of geothermal energy of the region are connected with increased heat flow in the ocean–continent transition zone (Sugrobov, 1982). In the general case, geological, hydrorheological, and geothermal conditions of the Kuril–Kamchatka island arc are favorable for HMS formation, in particular, within the Central and Eastern Kamchatka volcanic belts and on the Kuril Islands. Within this region, more than 20 high- and low-temperature systems can be distinguished (Pilipenko, 1998). Most geothermal areas are associated with Pleistocene–Holocene volcanoes. The host rocks are presented by volcanic rocks of Neogene–Quaternary age. A brief characterization of the major geothermal fields and hydrothermal–magmatic systems of the regions is given below.

The *Mutnovskoe GTF* is one of the most promising and best-studied fields in Kamchatka. It is located 70 km southwards from Petropavlovsk-Kamchatskii. Two geothermal stations with capacities of 12 and 40 MW are run here; they supply electricity into the general energy network of the Kamchatka Peninsula. A complex of volcanogenic and volcanogenic sedimentary rocks (of Oligocene–Miocene to Holocene age) participated in the formation of the Mutnovsko–Zhirovskii geothermal region (Deistvuyushchie vulkany ..., 1991). The presence of thermal waters with temperatures as high as 280°C deep in the system resulted in a significant transformation of rocks and the formation of zonal composition of the entire mass. The following zones are distinguished from bottom to top: middle-temperature propylites (quartz–epidote–chlorite and quartz–wairakite–prehnite), low-temperature propylites (illite, chlorite, and calcite), a zone of high-silicon zeolites and hydrothermal argillites, and a zone of sulfuric acid leaching (Slovtsov, 1994). We studied 75 samples taken from four boreholes and 45 samples from outcrops to determine the properties of the rocks.

Pauzhetskoe GTF is located in Southern Kamchatka on the slope of the Kambal'nii Ridge inside a large volcano-tectonic depression. In 1967, the first geothermal power plant in the Soviet Union (Pauzhetskaya) was launched here; today, its capacity is 11 MW. The field was formed in the tuff mass (N–Q) including lava flows and dykes of medium and basaltic compositions. The rocks were intensely altered by thermal waters with temperature up to 180–220°C. The rock mass of the field is characterized by a zonal structure. The following zones are distinguished from bottom to top: low-temperature propylitization zone (chlorite, calcite, and sericite), zeolitization zone (laumontite, chlorite, and corrensite), zones of high-silicon zeolites and argillic rocks (clinoptillolite, mordenite, geilandite, smectites, and opal). In decompacted zones, along which rising and effervescence occurs, metasomatites of quartz + adularia and quartz + adularia + wairakite + prehnite are formed composition. The system is in a regressive stage of development, which manifests itself in the overlapping of low-temperature mineral associations onto the earlier high-temperature ones (Struktura ..., 1993). The objects studied included approximately 200 hydrothermally altered samples, mostly tuffs, and to a smaller extent, effusive variations taken from six boreholes (depth up to 500 m) and from an outcrop located beyond the "flash" zones (21 samples).

Koshelevskaya HMS occupies the most southern position on the Kamchatka peninsula and is located on the slope of the volcano of the same name. The thermal fields of this high-temperature system are currently being actively studied by the researchers of the Laboratory of Geothermics, Institute of Volcanology and Seismology (Far East Division, Russian Academy of Sciences) and the Division of Engineering and Ecological Geology of Department of Geology of Moscow

State University. Several thermal fields are known within the Koshelev volcanic massif; two of those are very large (Verkhne- and Nizhne-Koshelevskoe fields). In the depths of the system, the temperature is as high as 250°C at the depth of 1100 m (Belousov and Sugrobov, 1976). The host rock consists of effusive and volcanoclastic rocks (N–Q). In all, 30 samples of andesites and tuffs that characterize the near-surface alterations occurring on the thermal fields were investigated.

Essovskaya HMS is located on the Sredinnyi Ridge on Kamchatka peninsula. This geological section is composed of Neogene–Pleistocene volcanogenic rocks (tuffs and lavas). There are many hot springs in this region with temperatures up to 95°C. The system has not been well studied thus far. Here, the total number of 23 tuff samples taken from outcrops were investigated.

The *Northern-Paramushirskaya HMS* is confined to the Vernadskii Ridge and is located in the northern part of Paramushir island. The geologic profile was studied up to the depth of 2500 m and is represented by Miocene–Pleistocene tuffs and tuffites (the major part of the profile) and andesite and andesite-basalt lavas (Rychagov et al., 2002). The following hydrothermal zones can be distinguished in structure of the HMS: middle-temperature propylite zone (quartz–chlorite–epidote–sericitic rocks), low-temperature propylite zone (quartz–adularia–hydromica rocks), and low-temperature opalites. Temperatures reach 180–260°C at depths of 1.5–2.5 km. The "flash" zones are individually distinguished; they are composed of quartz–adularia metasomatites. The hydrothermal system is in a progressive stage of evolution (Rychagov et al., 2005). The properties of 35 samples from four boreholes and 20 samples from outcrops that are not affected by hydrotherms were investigated.

The *Baranskogo HMS* is located on the slope of the Baranskogo volcano in the middle part of Iturup Island. It is a high-temperature hydrothermal system in a progressive stage of evolution with temperatures above 300°C at a depth of 1200 m (Rychagov et al., 1994). The host rocks are Pliocene-Quaternary tuffs and tuffites interbedded with lava flows and breached dykes. A shallow subvolcanic intrusion is assumed to be the heat source of the hydrothermal system. The entire rock section is impacted and altered by thermal fluids (as shown by the studied to depth up to 1200 m). The following alteration zones are distinguished (bottom to top): secondary quartzites, middle-temperature propylites (chlorite, quartz, wairakite, epidote, albite, and sericite), low-temperature propylite (zeolites, chlorite, and calcite), argillized propylites (mixed-layer clay minerals and calcite), the argillization zone, and zone of sulfuric acid leaching. The regular zoning is disturbed by "flash" zones with adularia, quartz, and wairakite. The properties of 250 samples from 11 boreholes were investigated (Frolova et al., 1999; Ladygin, Frolova, and Rychagov, 2000).

RESULTS AND DISCUSSION

Factors that have an effect on property alteration upon hydrothermal process. The character and intensity of petrophysical alteration of rocks under action of thermal waters depends on a number of factors including peculiarities of primary rocks (composition, structure, and properties), temperature, pressure, pH, and composition of thermal fluids; fluid phase (vapor–liquid), and the duration of the fluid–rock interaction. The contribution of each factor to changes in the properties of host rocks is considered below.

Peculiarities of the host rocks. The orientation and intensity of petrophysical alterations strongly depends on the specific rock undergoing alteration. Factors that are favorable for alteration are high porosity and permeability, microcracks, weak cementation, a high content of volcanic glass, and a basaltic composition of volcanites. The factors that impede hydrothermal alteration include host rocks with massive structures, low porosity, holocrystalline texture, and acidic composition of volcanites.

Host rocks in the HMS of the Kuril–Kamchatka region are mainly represented by volcanites that are composed of effusive and extrusive and volcaniclastic rocks of Neogene-Quaternary age. Significant differences were revealed when comparing the properties of these two rock groups (Fig. 1). Only fresh or slightly altered types were included in this comparison.

Effusive and extrusive rocks are formed during cooling and crystallization of lava, which is characterized by the formation of strong crystallization contacts between crystals. So the rocks are dense (ρ = 2.3–2.8 g/cm^3) with high strength (Rc = 70–250 MPa), high values of deformation properties (V_p > 4 km/s, E = 30–50 GPa), relatively low porosity and permeability (with the exception of the end parts of the flow). Quaternary lava flows generally form impermeable horizons within the HMS, but in some cases, they form fracture-type reservoirs.The zones of increased permeability may be associated with the system of primary petrogenetic fractures that are formed upon lava cooling, although the contribution of these fractures into the formation of permeability is generally insignificant. High permeability is characteristic only for the end parts of lava flows, which usually have a clumpy structure. Secondary fracturing is rather intensive. It may be of a tectonic nature, since the region under study is located in a tectonically active area. Furthermore, secondary fractions (hydrofault fractions) result from hydrothermal processes, when pressure generated by hydrotherms is higher than the strength of the rocks.

Volcanoclastites (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 as compared to effusive rocks. It was noted that Neogene rocks are

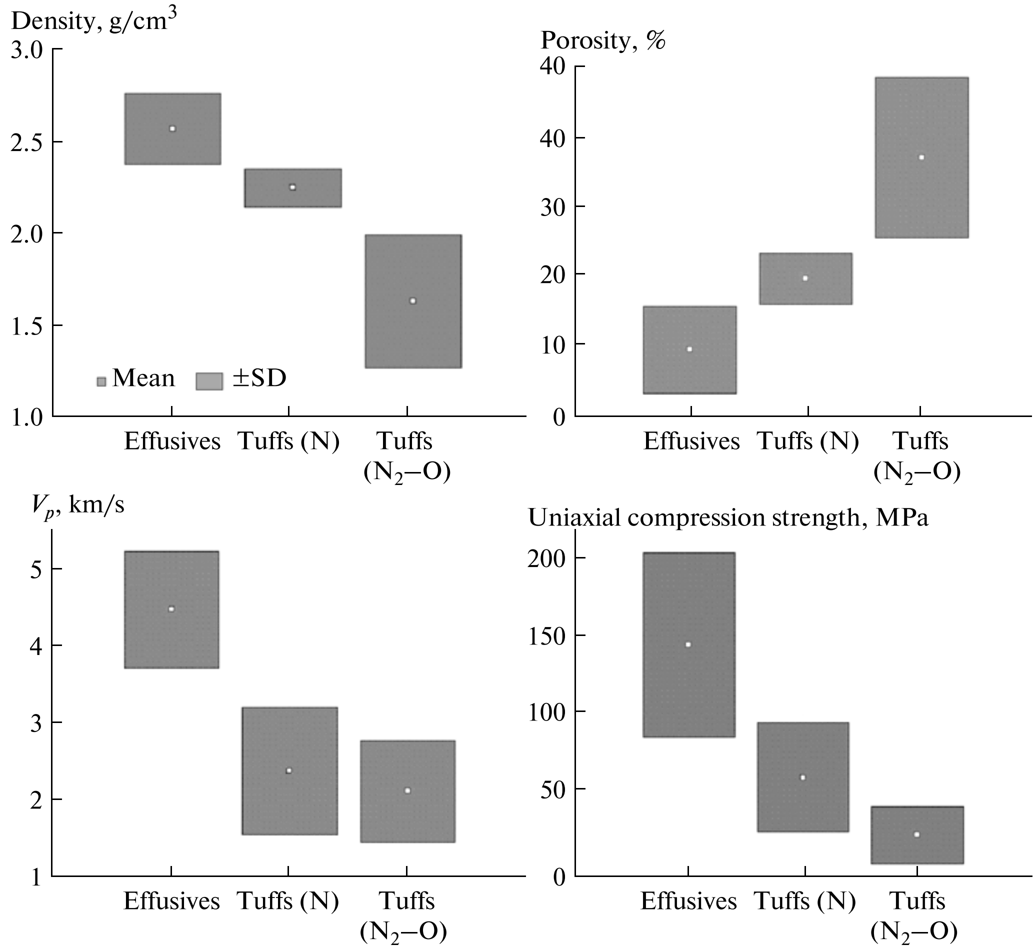

Fig. 1. Comparative characteristics of the properties of effusive rocks and tuffs. On the plots: point, the mean parameter value, box, the root mean square deviation. The number of samples: effusive rocks, 85; Neogene tuffs, 50; Pliocene–Pleistocene tuffs, 125.

more lithified and characterized by higher values of elasto-density and strength properties (mean values: $\rho = 2.2$ g/cm^3, $n = 20\%$, $V_p = 2.4$ km/s, $Rc = 60$ MPa) as compared with Pleistocene (Pliocene–Pleistocene) rocks (mean values: $\rho = 1.6$ g/cm^3, $n = 40\%$, $V_p = 2.1$ km/s, $Rc = 20$ MPa) (Fig. 1).

Tuffs and tuffites are the most common host rocks of hydrothermal systems in the Kuril–Kamchatka island arc. Typically, they form porous or fracture-porous reservoirs, but in some cases, they form impermeable horizons. A well-studied example is the Pauzhetskaya HMS. Its main reservoir is composed of weakly cemented coarse-grained tuffs. The caprock is composed of fine-grained tuffites. They are highly porous ($n = 30$–50%), but its water permeability is low due to ultra-small pore size, which makes porosity inefficient for fluids. Pore fluids react with the host rocks to gradually transform it into argillic rocks, but are not filtered through the stratum.

The Effect of PT conditions in a System

The temperature and pressure in hydrothermal systems have a significant effect on the alteration of the compositions and properties of the rocks. Volcanogenic rocks altered under the action of low- ($T < 150$°C) and high-temperature ($T > 150$°C) fluids considerably differ in terms of their properties (Fig. 2). In particular, tuffs altered under the action of high-temperature deep fluids are notable for their density ($\rho > 2.3$ g/cm^3, $n < 15\%$), high strength values ($Rc > 50$–70 MPa) and elastic wave velocity ($V_p > 4.0$ km/s). The strength of the tuffs that were subjected to the action of low-temperature near-surface fluids does not exceed 50 MPa, $V_p < 4.0$ km/s; density varies in a range of 1.0–2.0 g/cm^3 and porosity is higher than 20%. Low-temperature hydrothermalites are typically unstable in water; they soften or get soaked upon interaction with water. Moreover, low-temperature rocks are basic (W_H up to 5–6%), whereas high-temperature rocks contain no hygroscopic moisture.

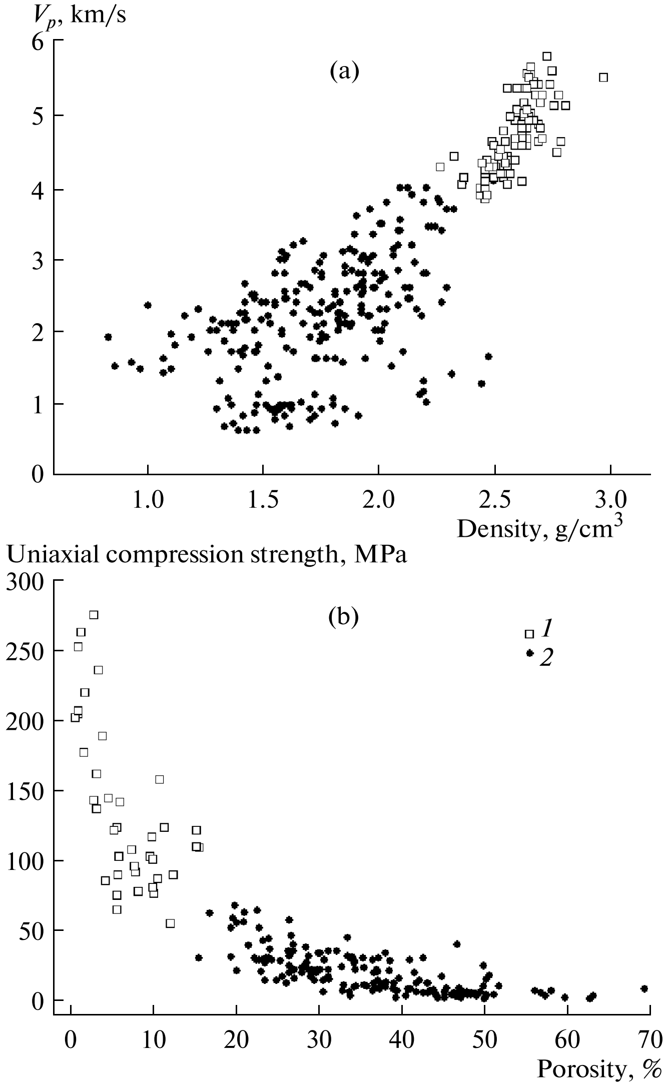

Fig. 2. Comparative characteristics of the tuffs altered under the action of high- and low-temperature thermal waters: (a) plot of longitudinal wave velocity as a function of density; (b) plot of uniaxial compression strength as a function of porosity. (*1*) Low-temperature transformations, (*2*) high-temperature transformations.

In order to construct the complete and consistent pattern of hydrothermal alterations on each field, first we studied the unaltered rocks that are common beyond the zone of impact of hydrotherms, followed by studying the rocks that underwent hydrothermal transformation.

Deep, high-temperature fluids cause an explicit sequence of alterations of properties: consolidation, hardening, a decrease in porosity and permeability, and removal of hygroscopic moisture. Initially porous, high-moisture, and hygroscopic tuffs with poor stability are transformed into dense and very strong formations. This tendency is observed for all major types of fluids (sodium chloride, sulfate–chloride, and hydrocarbonate) that are formed in deep zones of the HMS. The reinforcement of rocks primarily results from the formation of denser and stronger mineral phases, which fill the intergranular space, recrystallization of fine-grained glass basis into the secondary microcrystalline aggregate with phase contacts between the newly formed minerals. Among secondary minerals, the most significant role belongs to quartz, albite, epidote, prehnite, sericite, and adularia.

The tendency towards enhancement of the values of elasto-density and strength indices manifests itself to the largest degree in the formation of middle-temperature propylites and secondary quartzites. These transformations are observed on the Mutnovskaya, Baranskogo, and North-Paramushirskaya HMS (table). In particular, the density of tuffs increases from 1.1–1.7 in unaltered variations to 2.3–2.6 g/cm^3 in altered rocks; the density increases by an order of magnitude (to 100 MPa and higher) and V_p increases by a factor of 2–3 (from 1.5–2.5 to 4.5–5.5 km/s). In addition, the porosity decreases from 30–50% to several percent, water uptake considerably decreases (from 25–40% to several percent), and hydroscopic moisture vanishes.

Under the action of high-temperature fluids, effusive rocks become denser and stronger, but to a smaller extent than tuffs do. In certain cases, the magnitude of alteration can be so high that the rocks lose their primary features. In this case, the difference in properties between effusive and volcanoclastic rocks disappear.

The dynamics of the alteration of the properties of rocks that are induced by the actions of *low-temperature fluids* are more complicated and diverse. Low-temperature fluids are mostly formed in near-surface horizons of an HMS. The intensive mixing of ascending vapor hydrotherms with meteoric and near-surface acidic waters is typical of these horizons, which results in the prevalence of weakly acidic or acidic waters of different composition. Unlike high-temperature ones, these waters intensively leach minerals out, dissolve and transport chemical components, etc. The alteration of properties of rocks in this case depends to a large extent on the prevailing process, viz., the leaching of the rock, filling of pores and fractions, or metasomatic replacement of primary minerals for more stable neoformations. The leaching of rocks by acid fluids forms secondary porosity and lowers density, whereas the sedimentation of secondary minerals in pores leads to the opposite effect: the rocks become denser and their porosity and permeability decrease. Upon metasomatic replacement of primary minerals, the composition of secondary minerals has a considerable effect on property alteration. Thus, the effects of low-temperature fluids on the properties of volcanites is ambiguous and requires thorough study and analysis of the geologo-structural, petrological, hydrogeochemical, and other features in each particular case.

The chemical composition of thermal fluids. During low-temperature processes, the chemical composition of thermal waters and their acidity–alkalinity have a considerable effect on the alteration of rock properties. Various mineral associations result from contact with low-temperature waters with different parameters, such as siliceous minerals (opal, tridymite, cristobalite, chalcedony, and quartz) and argillic minerals (kaolinite, halloysite, montmorillonite, mixed-layer) zeolites, and alunite, which have different effects on rock properties.

Opalite zone. Opalites are formed under the action of sulfuric acid leaching of rocks induced by subsurface low-temperature sulfate (chloride–sulfate) waters with pHs of 1–3. They widely occur and form blanket-like covering within the Mutnovskaya, North-Paramushirskaya, and Koshelevskaya HMS, as well as the Baranskogo HMS. Under the action of sulfuric acid leaching, the major rock-forming components are removed from the host rocks (with the exception of Si), which are transformed into porous monosilicon formations. Silica minerals form pseudomorphoses with respect to primary components. The volcanic glass, which usually forms cement in tuffs and is found in the matrix of effusives, is replaced by cryptocrystalline aggregates of crystobalite. The properties of the rocks change rather consistently; however, the sequence of the alteration of properties in tuffs and effusives is different. Under the action of opalitization, weakly cemented porous tuffs become stronger; their elastic characteristics are enhanced, despite the fact that the density does not increase and porosity remains high. The main reason for this is the formation of a rigid siliceous framework, which is still porous, but stronger as compared with the weak primary cementation of tuffs. In particular, unaltered tuffs from the Mutnovskaya HMS are characterized by the following values of property indices: $\rho = 0.9–1.5$ g/cm^3, $n = 40–60\%$, $V_p = 1.5–2.2$ km/s, and $Rc \leq 10$ MPa. For rocks that are transformed into opalites these properties are as follows: $\rho = 1.5–1.9$ g/cm^3, $n = 30–40\%$, $V_p = 2.0–3.3$ km/s, $Rc = 20–30$ MPa (Frolova and Ladygin, 2008). In certain cases, sedimentation of silica takes place and the pores are filled with fine crystalline quartz or chalcedony, resulting in the formation of denser ($n = 10\%$) and stronger ($Rc = 50$ MPa) rocks. Hematite and iron hydroxides that give brown and sometimes mottled coloration to the rocks and induce a certain increase in density are frequently formed in association with opalites.

An opposite tendency (a decrease in density, strength, elastic characteristics; secondary porosity formation) is observed upon opalitization of lithified dense tuffs and effusive rocks. In particular, for andesites from the thermal fields of the Koshelevskaya HMS a sequential series is formed in terms of the degree of rock alteration: from fresh andesite to completely transformed rock (white light and porous opalite) (Frolova et al, 2010). With the increasing degree of transformation of rocks, microlites and volcanic glass are transformed into cryptocrystalline crystobalite and opal. Phenocrysts are leached out and pseudomorphically replaced by fine-crystalline crystobalite aggregates, sometimes with impurities of kaolinite. Kaolinite is typical of the intermediate stages of transformation, while the final product of alteration is almost completely composed of crystobalite. The leaching of primary components results in the formation of secondary porosity (andesites, 8% and opalites, 37%); the specific density decreases from 2.85 to 2.31 g/cm^3, the values of elasto-density properties decrease (Fig. 3), and the uniaxial compression strength decreases by four times (from 120 to 30 MPa). A decrease in Poisson's ratio from 0.31 to 0.14 is observed. It occurs due to the formation of an "openwork" silicaceous structure, in which lateral deformations are insignificant; it is fragile upon decomposition. The magnetic susceptibility upon the formation of opatites decreases by three orders of magnitude (from several tens to several SI units × 10^{-3}), which is caused by decomposition of ore and dark-colored minerals with ferromagnetic and paramagnetic properties and the formation of siliceous minerals with diamagnetic properties.

A comparative characterization of the properties of unaltered tuffs and mid-temperature propylites

Rock	ρ, g/cm^3	W, %	V_p, km/s	Rc, MPa	Number of samples
North Paramushirskaya HMS					
Unaltered tuffs	1.3*/1.1–1.5	39	1.4/1.3–1.7	6/3–10	20
Mid-temperature propylites	2.6	<1	4.25/4.0–4.5	73/50–95	5
Mutnovskaya HMS					
Unaltered tuffs	1.4/0.9–1.6	25	1.8/1.3–2.4	5/1–12	8
Mid-temperature propylites	2.6/2.3–2.7	1	4.7/3.9–5.6	90/60–190	70
HMS of Baranovskogo volcano					
Unaltered tuffs	1.5/1.2–1.7	23	1.7/1.4–1.9	20/5–35	10
Mid-temperature propylites	2.3/2.1–2.7	5	3.8/3–5.2	75/40–130	28
Secondary quarzites	2.5	3	4.3/4–4.5	115/90–160	7

* Above the line, the mean parameter value; below the line, the minimum and maximum values.

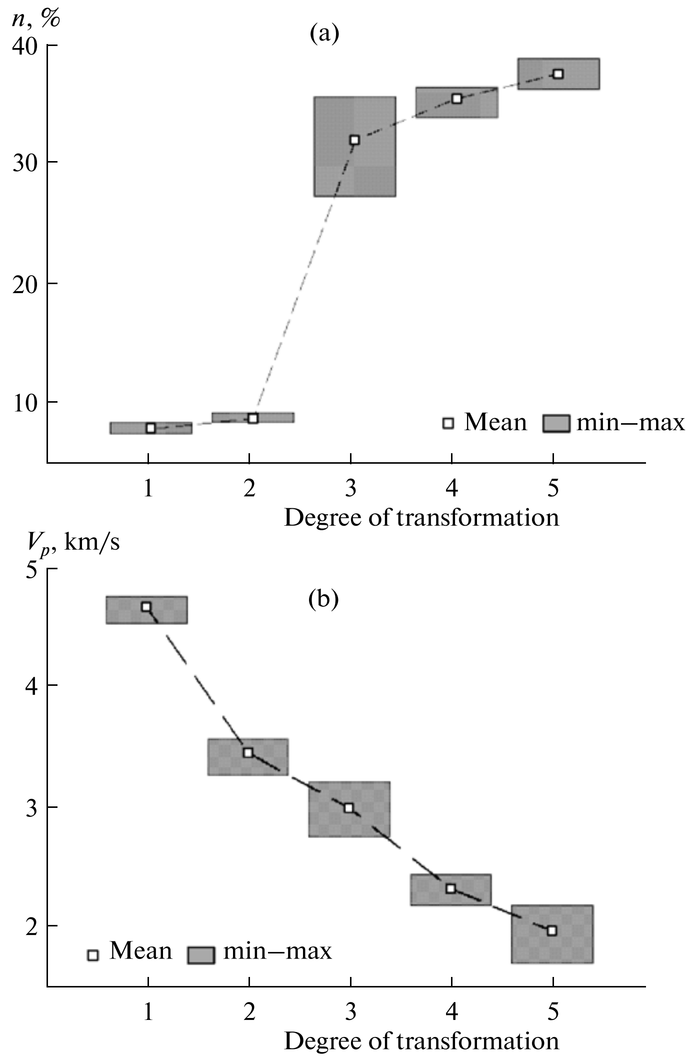

Fig. 3. The alteration of properties of andesites under the action of sulfuric acid leaching in the Verkhnekoshelevskoe thermal field: (a) porosity; (b) velocity of propagation of longitudinal waves; (*1*) fresh andesites (SiO_2 55%); (*2*) altered andesites (SiO_2 70%); (*3–5*) opalites (SiO_2 86–91%).

Kaolinite zone. An increase in pH to 4–5 results in the formation of kaolinite, which causes a reduction of the physico–mechanical properties of volcanites (Rc ~ 10 MPa, V_p = 1.5–2.0 km/s), the formation of hygroscopic moisture (1–5%), and a decrease in permeability. In these conditions, most tuffs are replaced by kaolinite and opal; in addition, iron hydroxide and dioctahedral montmorrilonite are frequently present. The newly formed minerals are basically developed in the cementing rock, so that the fragments of plagioclase and pyroxene remain relatively fresh. Tuffs are light (ρ = 1.6–1.7 g/cm^3) and highly porous (n = 35–40%) with V_p of ~ 2.0 km/s and low strength values Rc = 7–20 MPa. Upon progressing acidification of the solution, kaolinite is dissolved and replaced by halloysite to form a completely transformed white rock that is very light (ρ = 1.35 g/cm^3, highly porous (n = 47%), moisture-absorbing (W = 21%), and low-strength (Rc = 10 MPa); it weakens by 50% as it is saturated with water.

Smectite zone. Argillaceous minerals of the smectite group are formed under the action of hydrocarbonaceous fluid with a pH of 5–6. This zone was revealed in all the hydrothermal systems under study. Smectite pseudomorphically replaces primary minerals and develops in volcanic glass, which results in a decrease in the physical and chemical properties of the rocks (Rc = 10–20 MPa, V_p = 2 km/s) and the emergence of hydroscopic moisture (W_H = 2–6%). Argillized rocks lose their strength upon interaction with water; they become softer and become soaked in certain cases. In addition, smectites considerably reduce the permeability of rocks, despite their high porosity (n = 35–50%). Very often entire masses of volcanogenic rocks are transformed into argillaceous masses, with the replacement being of a pseudomorphous character. The argillization zone frequently acts as an upper impermeable horizon of an HMS.

Zone of high-silicon zeolites. An increase in the pH of a fluid to the values that are typical of an alkaline medium result in the formation of high-silicon zeolites associated with smectites. High-silicon zeolites (clinoptillolite, mordenite, and geilandite) frequently form film cement in tuffs; the interfragment space remains unoccupied. These rocks are highly porous and are characterized by low density values. They can be permeable, but permeability decreases in the presence of smectite.

The *zone of zeolite propylites* is formed under the action of alkaline fluids with temperatures of ~200°C. This zone commonly occurs in the Pauzhetskaya HMS, where tuffs are completely transformed into chlorite(corrensite)–laumontite rocks with a secondary granoblastic–micropoikilite texture. These rocks are highly porous (n = 35–40%), low-strength (Rc < 100 MPa), and are characterized by anomalously low values of V_p ~ 1 km/s, which is likely to be conditioned by the special microporous structure of the chlorite–laumontite matrix of the rock with weak contact between the microcrystals, which increases the time of passage of elastic waves.

In general, zeolitization and argillization facilitate a decrease in the elasto-density and strength parameters. In contrast, under the action of sulfuric acid leaching, as a result of the development of silicaceous minerals, the elastic and strength parameters of tuffs increase, despite the increase in porosity.

Phase state of the fluid. The zones of liquid–vapor phase transition are special in terms of thermodynamic and geochemical regimens. They may be confined to open tectonic disturbances, where the lithostatic pressure drops abruptly, resulting in the effervescence of hydrotherms. Effervescence may also occur as hydrotherms lift to the surface (at the point of intersection with the boiling point at the specified pressure, temperature, and composition of the fluid). The boiling process is accompanied by heat loss and decrease in temperature, separation of the gas component, and alkalization of the solution. The "flash" zones are formed at different depths. They are fixed by quartz-adularia and wairakite–epidote–quartz–adularia mineral associations, which are based on fine- and cryptocrystalline (less frequently, mosaic) quartz and almost always on adularia. Intensively silified rocks are notable for high density ($\rho = 2.3–2.4$ g/cm^3), higher strength ($Rc > 80–100$ MPa), high values of $V_p = 4.0–4.2$ km/s, and the absence of magnetic properties, since the main rock-forming mineral, quartz, is a dielectric. Meanwhile, the presence of large leaching voids that are typical of this zone has an opposite effect on these properties. In this case, the formation of secondary porosity decreases the density ($\rho < 2$ g/cm^3), elastic ($V_p \sim 3.0–3.5$ km/s), and strength ($Rc = 40$ MPa) characteristics of the rocks.

The duration of the hydrothermal process. The variability of rock properties within an HMS depends on the duration of the hydrothermal process. This becomes clear when comparing three well-studied HMSs: Pauzhetskaya, Mutnovskaya, and Baranskogo HMSs that functioned during different periods and are at different stages of development (Rychagov et al., 2005). The Baranskogo HMS is the youngest, which is in a progressive stage. The hydrothermal zones of this system (in particular, the low-temperature ones) are characterized by a wide range of values of physico–mechanical parameters, which is due to the considerable effect of primary petrographic nonuniformities, as well as the irregularity and incompleteness of hydrothermal transformations. Within one zone, both unaltered and completely transformed rocks possessing different properties may occur. The Mutnovskaya HMS is in an extreme stage of its development. Hydrothermal zones in terms of their petrophysical parameters are isolated into separate groups. Among the systems under consideration, the Pauzhetskaya HMS is the most ancient one. It is currently in a regressive stage of development; the superposition of low-temperature transformation on the earlier high-temperature ones is typical of it. A more intensive and long-term process of rock transformation, which resulted in the formation of hydrothermal zones that are uniform in terms of composition and properties, corresponds to the regressive stage of development. Thus, in the course of the evolution of the systems, the difference in the properties between the zones increases and the uniformity of the rocks within each zone increases.

CONCLUSIONS

1. Hydrothermal–magmatic systems of the Kuril–Kamchatka island arc were formed in volcanogenic rocks of Neogene–Quaternary age. The properties of the host rocks (effusive and volcanoclasic rocks) are considerably different from the very beginning. Effusive rocks are characterized by higher values of density, strength, and deformation parameters; they are less porous and permeable.

2. The spectrum of thermodynamic and physical and chemical conditions in which hydrothermal transformations occur is immensely wide, which results in the variability of forming rocks. Volcanogenic rocks are transformed into totally new hydrothermal–metasomatic aggregates, such as monoquartzites, different propylites, zeolite formations, argillite-altered rocks, opalites, quartz-adularia metasomatites, etc.

3. By acting on the host rocks, thermal waters result in considerable and multidirectional changes in their properties. The dynamics of changes in the properties of rocks during hydrothermal processes depend on a number of factors, among which the most significant ones are the features of the primary rock; *PT* conditions in the system; the chemical composition, pH and phase state of the fluid; and the duration of the fluid–rock interaction.

4. Almost regardless of their composition, high-temperature deep fluids cause such alterations as consolidation, hardening, increase in deformation parameters, decrease in porosity and permeability, and removal of hygroscopic moisture. These alterations of properties are observed for both effusive rocks and tuffs; however, in tuffs the alteration is pronounced more clearly. The reasons for this are as follows: the interfragment/intercrystalline space is filled with secondary minerals, recrystallization of the basis into a secondary microaggregate consisting of denser and stronger minerals, and the formation of strong phase contacts between newly formed crystals.

5. The dynamics of the alteration of the properties of rocks caused by the action of low-temperature fluids is more complicated and versatile. It may be different for tuffs and effusive rocks. The chemical composition and acidity/alkalinity of thermal waters have a significant effect on the alteration of the properties of rocks during low-temperature hydrothermal processes.

6. In the course of evolution of an HMS, the differentiation of the properties increases in different hydrothermal zones and the uniformity of the rocks within each zone increases.

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