ISSN 0742-0463, Journal of Volcanology and Seismology, 2016, Vol. 10, No. 3, pp. 170–187. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © Yu.V. Frolova, S.N. Rychagov, V.M. Ladygin, M.V. Luchko, M.S. Chernov, I.A. Boikova, 2016, published in Vulkanologiya i Seismologiya, 2016, No. 3, pp. 22–40.

Variation in the Physical and Mechanical Properties of Rocks: The North Paramushir Hydrothermal Magmatic System, Kuril Islands

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Received January 20, 2015

Abstract—This study is concerned with structural and mineralogic transformations and changes in the physical and mechanical properties of volcanogenic sedimentary rocks in the North Paramushir hydrothermal magmatic system as a result of the interaction with thermal waters of various compositions and origins. We identified the following hydrothermal metasomatic facies that developed in tuffites and tuffs: opalites (monoopalite, opal–clay, and opal–alunite), as well as low- and moderate-temperature propylites. We show the position of each new facies in the structure of the hydrothermal magmatic system. We obtained correlative relationships of the physical and mechanical properties of the rock to the intensity and character of secondary alteration. It is pointed out that all of these rocks obey a common trend in the interrelationships between their properties, which may provide evidence of a common origin and progressive direction of hydrothermal processes in the interior of the North Paramushir system.

DOI: 10.1134/S0742046316030039

INTRODUCTION

The study of the physical and mechanical properties of the rocks that make up the structure of a hydrothermal (hydrothermal magmatic) system must necessarily deal with several fundamental scientific and technical problems. The ascent of hot gas-charged hydrothermal fluids in the crust, the circulation of thermal and meteoric waters in the rocks, the release of steam and gas with intensive filtration of mobile phases through rocks, and metasomatic processes all considerably affect the geological space. The great diversity of characteristics that are found in hydrothermal magmatic systems is of great interest to specialists in various disciplines (Belousov, 1978; Pek, 1989; Corbett and Leach, 1998). Apart from the determination of the mechanical and physical properties of rocks, petrophysical studies in this line of research also have to deal with several geological issues, including the generation of hydrothermal magmatic systems and the characterization of the material composition for primary and new rocks. This multidisciplinary approach is able to acquire extensive data on hydrothermal magmatic systems and the geothermal deposits that are formed in their interiors (Belousov et al., 2002; Frolova et al., 2014; Lutz et al., 2011).

The geothermal energy industry has been actively developing in over 70 countries during recent decades (Lund and Bertani, 2010). The exploration and exploitation of geothermal fields must be based on the study of the engineering geological characteristics of the rocks that control geothermal reservoirs, the zones of downward filtration of cold waters, the regions of hydrothermal boiling, etc. Data on the physical and mechanical properties of rocks are also required for the construction of geothermal power stations and the management of geothermal facilities. In addition, recent research showed that hydrothermal magmatic systems typically show high dynamics of endogenous and exogenous processes, which leads to the redistribution of water flows in the zone of hypergenesis and in the interiors of the systems, to local changes in the relief, and not infrequently to the generation of landslides, which pose a serious hazard to development in geothermal areas. The continuing improvement in the exploitation of each geothermal field and the prevention of human-induced disasters in geothermal areas largely depend on detailed and multidisciplinary studies on the physical and mechanical properties of rocks.

The northern part of Paramushir Island has been studied by many investigators, in the first place in connection with the activity of Ebeko, which is one of the most dangerous explosive volcanoes on the Kuril Islands (Kotenko and Kotenko, 2010). Great interest has also been shown in the discharge of acid and ultra-acid metalliferous hydrothermal waters by the Yur'evskii springs and in the Ebeko crater zone (Nikitina, 1978). The evolution of magmatism, the formation of the Vernadskii volcanic mountain range, and its hydrothermal systems were studied by G.S. Gorshkov, E.K. Markhinin, V.I. Fedorchenko, and S.I. Naboko. The more recent studies of the area resulted in identification of the North Paramushir hydrothermal magmatic system and the North Kuril geothermal field with potential reserves of up to 100 MW of electricity (Belousov et al., 2002), with the geological reference section of the system and the field being reconstructed down to a depth of 2500 m (Rychagov et al., 2002); geological features have been identified that hold promise for development of the field. However, petrophysical research has been somewhat neglected, with scanty information being available on the physical and mechanical properties of the rocks that make up the well GP-3 section (Rychagov et al., 2002) and on the physical properties of the hydrothermally altered rocks of Ebeko Volcano (Shevko et al., 2013).

We have acquired new extensive data by studying cores that were extracted from additional wells (see below) and by sampling in geological transects in order to study the effects of hydrothermal metasomatic processes on the structure, texture, and properties of volcanogenic rocks.

THE GEOLOGY AND GEOTHERMICS OF THE NORTH PARAMUSHIR HYDROTHERMAL MAGMATIC SYSTEM

The geological structure of the area. There have been many studies of the geological structure of Paramushir Island (*Geologo-geofizicheskii* ..., 1987; *Opyt* ..., 1966). Detailed information on the geology of the North Paramushir area and the eponymous hydrothermal magmatic system can be found in (Melekestsev et al., 1994; Belousov et al., 2002). The base of the geological section consists of volcanogenic sedimentary deposits of the Okhotsk Formation ($N_1^3-N_2^1$) and of the Oceanic Formation ((N_2^{2-3})) (Fig. 1). The basement rocks are cut through by dikes and sills of intermediate and basic compositions, which are probably of Upper Pliocene and Quaternary ages. The Pleistocene to Holocene phase saw the formation of the Vernadskii Range, which is composed of andesitic volcanoes in the south and basaltic andesite volcanoes in the north. The Holocene basaltic andesite Ebeko and Neozhidannyi volcanoes belong to the North Paramushir hydrothermal magmatic system, which is confined to a ring feature at an intersection of longitudinal and transverse regional faults.

A geological and geothermal characterization of the North Paramushir hydrothermal magmatic system. It is commonly thought that this major, long-lived, high-temperature convective system is at the progressive phase of its evolution (Rychagov et al., 2002). That means that the rocks in its interior continue to be further heated. The source of the heat supply for the system is diorite or gabbro–diorite bodies that are related to a peripheral magma chamber that lies at depths of over 3–5 km (Rychagov, 2003). A detailed study of the hydrogeochemistry and hydrodynamics in northern Paramushir Island allowed us to identify, in addition to the central rising hydrothermal flow that is discharged in the crater region of Ebeko Volcano, two lateral flows as well, viz., a northwesterly and a southeasterly one. The flows are generated by deep-seated chloride sodium waters that are heated by subvolcanic bodies, are saturated with acid magmatic gases, and are rising to the ground surface along a system of permeable zones, as well as being filtered in volcanogenic sedimentary rocks. The high-temperature brine reacts with the host rocks as it is moving and some boiling occurs in some regions with subsequent steam condensation in the top of liquid–steam transition zones; secondary sulfate waters are formed in the zone of condensation. These waters are discharged and are mixed with meteoric waters at the periphery of the system. It is supposed that the waters of the southeasterly flow that are circulating at depths of 1500–2500 m have temperatures of 180–250°C (Belousov et al., 2002).

Hydrothermal and metasomatic alteration. The rocks have experienced considerable changes due to thermal water, with the reference section (well GP-3) being a good example. Moderate-temperature propylites of quartz–chlorite–epidote–muscovite compositions are being formed on lithic–crystal tuffs and intrusive breccias (the depth interval between 2500 and 1700 m). This is a zone of slow circulation of chloride sodium waters that frequently occurs in the apical parts of diorite or gabbro–diorite subvolcanic bodies. Moderate-temperature, quartz–adularia–hydromica metasomatites are generated in the depth interval of 1650–750 m on lithic–crystal variegated tuffs and the base of the tuffite rock sequence. The metasomatites resulted from active circulation of carbonaceous alkaline or neutral hydrothermal fluids through fissures and pores. At the top of this zonality are low-temperature, opal–cristobalite–tridymite–chalcedony metasomatites with ore mineral inclusions (750–100 m). The latter rocks typically show cryptocrystalline textures of siliceous minerals, with this being the response of the system to rapid cooling in the zone of boiling brine. A liquid–steam transition zone was identified at the boundary between the second and the upper zone with quartz–adularia metasomatites containing native metals and intermetallic compounds. The following zones of low-temperature propylitization with superimposed argillization and sulfate leaching are identified in the well 4GP section down to a depth of 1300 m at the periphery of the North Paramushir system (upwards): an illite–montmorillonite–prenite–zeolite zone, an illite–chlorite–calcareous zone, and a smectite–celadonite–opal zone (Boikova, 2011). Opal–kaolinite–alunite rocks (opalites) are developed in craters and fumarole fields of volcanoes at the Vernadskii Range owing to intensive sulfate leaching of basaltic andesites (*Opyt* ..., 1966). How-

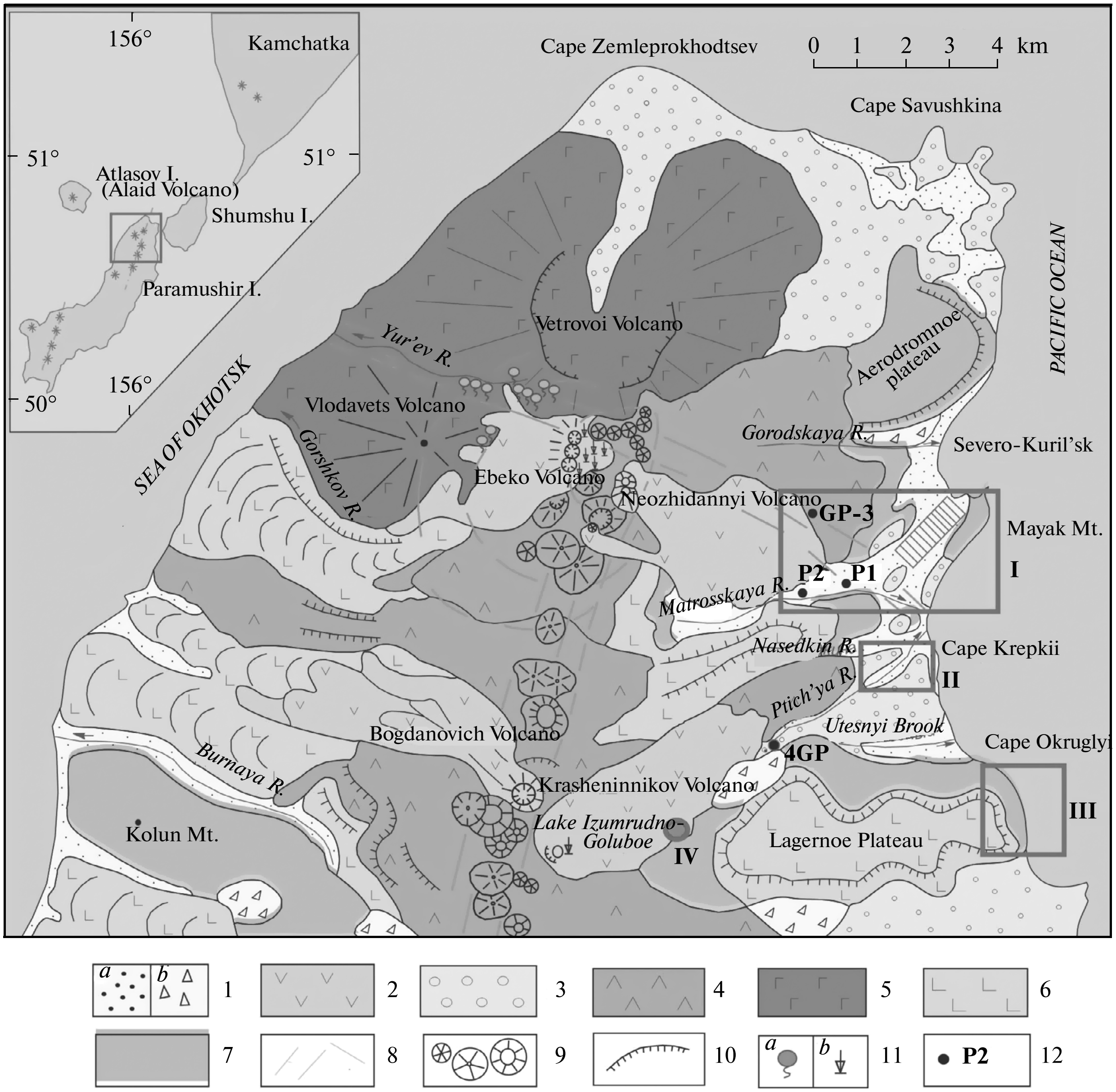

Fig. 1. A schematic geological map for northern Paramushir Island (after V.L. Leonov with additions and modifications). (1) present-day alluvial, marine, and lacustrine deposits (*a*), landslide deposits (*b*); (2) andesitic and basaltic andesite lavas (Q_4); (3) glacial deposits (Q_3^4); (4) andesite lavas (Q_3); (5) andesite and basaltic andesite lavas (($N_2^2 - Q_1$); (6) basaltic lavas, tuffs, and tuff breccias (Q_{1-2}); (7) unstratified volcanogenic sedimentary deposits and subvolcanic bodies, Okhotsk and Oceanic Formations ($N_1^2 - N_2$); (8) tectonic discontinuities of the linear and ring types; (9) minor volcanoes, lava and cinder cones at the axial part of Vernadskii Range; (10) morphologically expressed scarps and boundaries of erosion calderas; (11) thermal springs (*a*) and fumaroles (*b*); (12) geothermal wells and their identification numbers. Roman numerals mark sampling sites.

ever, leaching also affects the volcanogenic sedimentary rocks that underlie the Quaternary volcanic rocks. The opalites make up a connected zone that is 1–1.5 km wide and up to 200–250 m thick that extends along the axial part of the Vernadskii Range. These rocks are host to sulfur and sulfur–silver deposits that were discovered in the southern part of the range (Vlasov, 1958). The rocks thus serve as a reliable indicator of discharge regions for metalliferous hydrothermal fluids that are generated directly above the magma chambers owing to the actions of acid gases (primarily, CO_2, H_2S, SO_2, and HCl).

THE METHOD OF STUDY

The raw materials for the study were samples from bedrock exposures and the core samples from several wells (monoliths at least 12 × 12 × 12 cm in size) (see Fig. 1). Detailed sampling was carried out in the section of volcanogenic sedimentary deposits on Cape Okruglyi that are thought to be beyond the zone of influence of hydrothermal metasomatism. A total of 63 samples were investigated. We also used bore mud from wells 4GP and GP-3 to study the chemical composition of the rocks.

Workers at the Chair of Engineering and Ecologic Geology in the Department of Geology of Moscow State University used rock and core monoliths to make specimens of regular geometric shapes in the form of rectangular prisms (a = b = 3–4 cm) or cylinders (h = d = 3–4 cm). Each monolith or a core provided two to five specimens. The following physical and mechanical properties were determined or calculated: density (ρ), the density of solid particles (mineral density, Analyst M.V. Kopteva-Dvornikova) (ρ_s), total (n) and open (n_o) porosity, water absorption (W_{absorp}), the velocities of compressional (V_p) and shear (V_s) waves in dry and saturated rocks, magnetic susceptibility (χ), uniaxial compressive strength in dry (R_c) and water-saturated (R_{cw}) state, and the coefficient of softening ($K_{soft} = R_{cw}/R_c$). All determinations were made following the standard procedures (Frolova, 2015). The study of the rock properties was accompanied by investigations of the mineral composition, structure, and morphology of the pore space using the methods of optical microscopy (OLYMPUS and POLAM L-211 microscopes; over 100 polished sections are described), X-ray diffractometry (DRON-6, Analysts: Senior Researcher V.V. Krupskaya and Senior Teacher V.L. Kosorukov, 15 samples were investigated), and electron microscopy (LEO 1450VP with an INCA 300 microprobe analyzer, Operator: Senior Researcher, Cand. Sci. (Geol.–Mineral.) M.S. Chernov; and Jeol JSM-6430, Analyst E.V. Guseva; 10 samples were investigated). The chemical analyses were performed at the Analytical Center of the Institute of Volcanology and Seismology at the Far East Branch of the Russian Academy of Sciences (IV&S FEB RAS) using an S4 PIONEER X-ray fluorescence spectrometer (The director of the AC is E.V. Kartasheva). The statistical data processing used the Statistika software. Below we discuss the physical and mechanical properties of the volcanogenic sedimentary rocks that were sampled in northern Paramushir and the variation of properties under hydrothermal processes in the series from opalites to moderate-temperature propylites.

VOLCANOGENIC SEDIMENTARY ROCKS ON CAPE OKRUGLYI

The upper part of the Okhotsk Formation ($N_1^3 - N_2^1$) is exposed on Cape Okruglyi. This rock sequence has a layered structure and consists of alternating beds of psammite and aleurite tuffites and tuffs, as well as of poorly consolidated tuff sandstone and tuff gravelites that dip east in a monoclinic manner at angles of 5° to 10° (Figs. 2a and 2b). The visible thickness of these deposits is 500 m. The rocks are beige to grey-beige in color, have a crystalline and vitroclastic texture, and a comparatively homogeneous massive or stratified structure. The main rock-forming components include plagioclase crystal clasts, with lesser amounts of grains of quartz and mafic minerals (pyroxene and amphibole). There are large amounts of fragments of siliceous frustules that have oval shapes and are up to 0.05–0.1 mm across (Figs. 3a, 3b, 3c, and 3d). This furnishes evidence of marine conditions that prevailed during the formation of the rocks. One encounters individual glauconite grains. Fine-grained volcanic glass serves as the cementing mass. This glass is occasionally replaced with cristobalite and clay minerals (hydromica and smectite). The replacement process can be clearly seen on SEM images: the polished surface of volcanic glass fragments shows lamellate and laminated particles of clay minerals. The polished sections show thin (1–2 μm), sinuous microcracks that frequently occur at the contact between crystal clasts and the cementing vitreous mass.

The rocks are comparatively poorly stratified. From the engineering geological point of view, they are semi-bedrock soils (R_{cw} < 5 MPa), have high porosity and low density and strength (Table 1). The density values vary between 1.00 and 1.48 g/cm^3. The mineral density is within the 2.58–2.79 g/cm^3 range. The observed scatter of ρ_s is due to the variability of the mineral compositions, in particular, the presence of mafic minerals and pyrite makes this quantity higher, as it must be. The total porosity reaches 60%, with most of the pores (85–90%) being open, i.e., they are connected to form a network of channels that can transmit water. The porosity is very fine, with pore diameters varying between 1–2 and 10–20 microns. Compressional velocity is low (between 0.7 and 1.7 km/s, but mostly 1.4–1.5 km/s); this is consistent with the high porosity of the rocks. Under water saturation, the values of this parameter vary both ways, sometimes decreasing and in other cases increasing. The decrease in V_p seems to be due to the presence of clay minerals whose particles adsorb water, forming a layer of coherent (adsorption) and osmotic water, which makes for lower compressional velocities. The strength under uniaxial compression varies between 3 and 10 MPa in air-dried specimens. When saturated with water, the strength of the tuffites decreases by 50–85%, because that of the intergranular contacts is greatly affected by water (R_{cw} < 4 MPa; K_{soft} < 0.5).

To sum up, the Okruglyi volcanogenic sedimentary rocks are characterized by a high open porosity, low lithification, and low strength. The presence of insignificant amounts of cristobalite, clay minerals, and pyrite in the rocks is related to regional epigenetic processes, while no signs of hydrothermal metasomatic

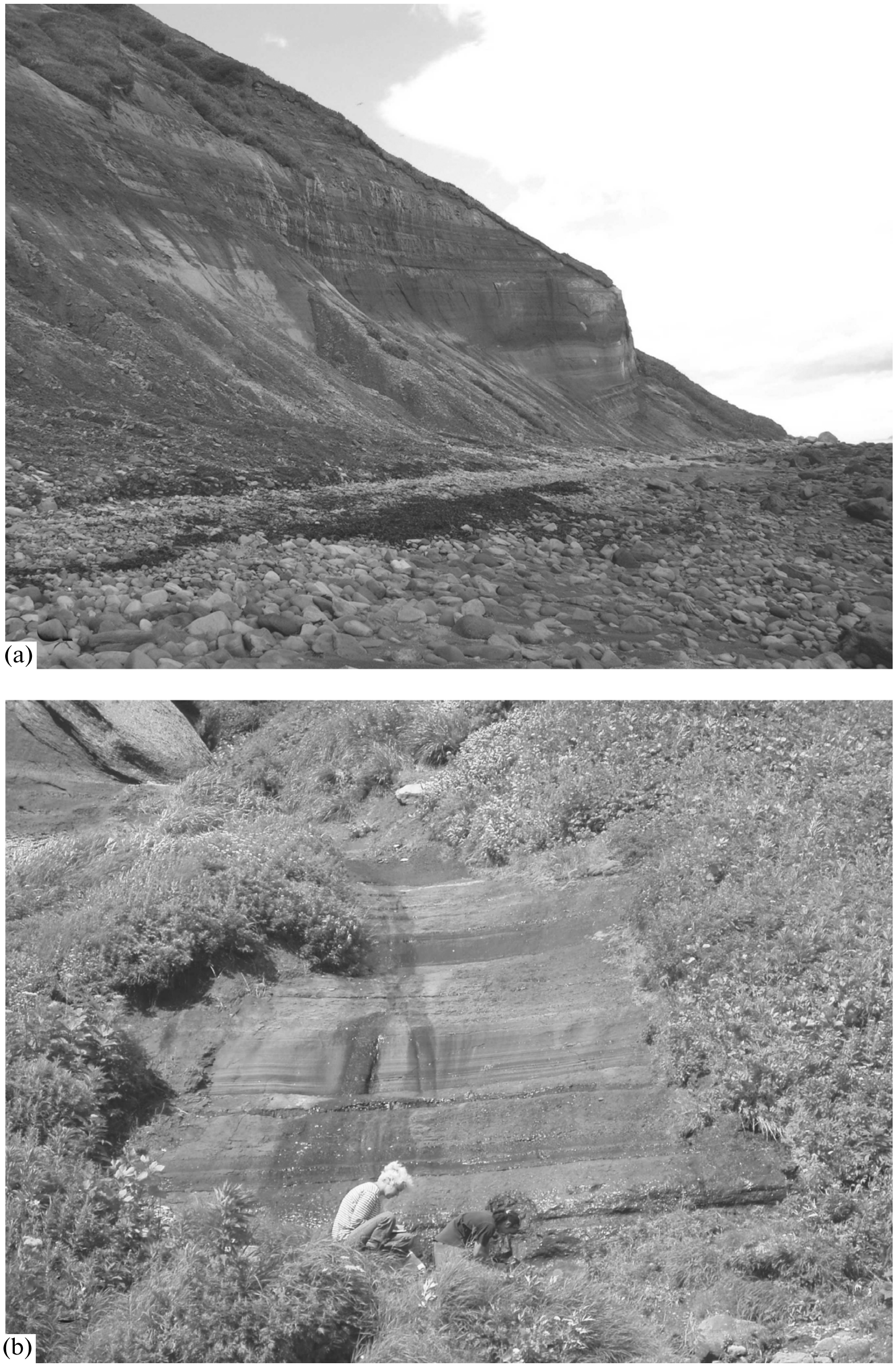

Fig. 2. Exposures of the Okhotsk Formation on Cape Okruglyi.
(a) overall view, (b) sampling site. Photographed by I.A. Boikova, 2005.

alteration have been detected. This circumstance, and the wide occurrence of tuffites and tuffs in the area of the North Paramushir hydrothermal magmatic system, enable us to treat these rocks as the primary ones in studies of the character and intensity of their transformations in the interior of the system.

OPALITES

The North Paramushir hydrothermal magmatic system contains extensive opalites, which occur on volcanic and volcanogenic sedimentary rocks. Of these, one distinguishes mono-opalic, opal-clay, and quartz-alunitic rocks.

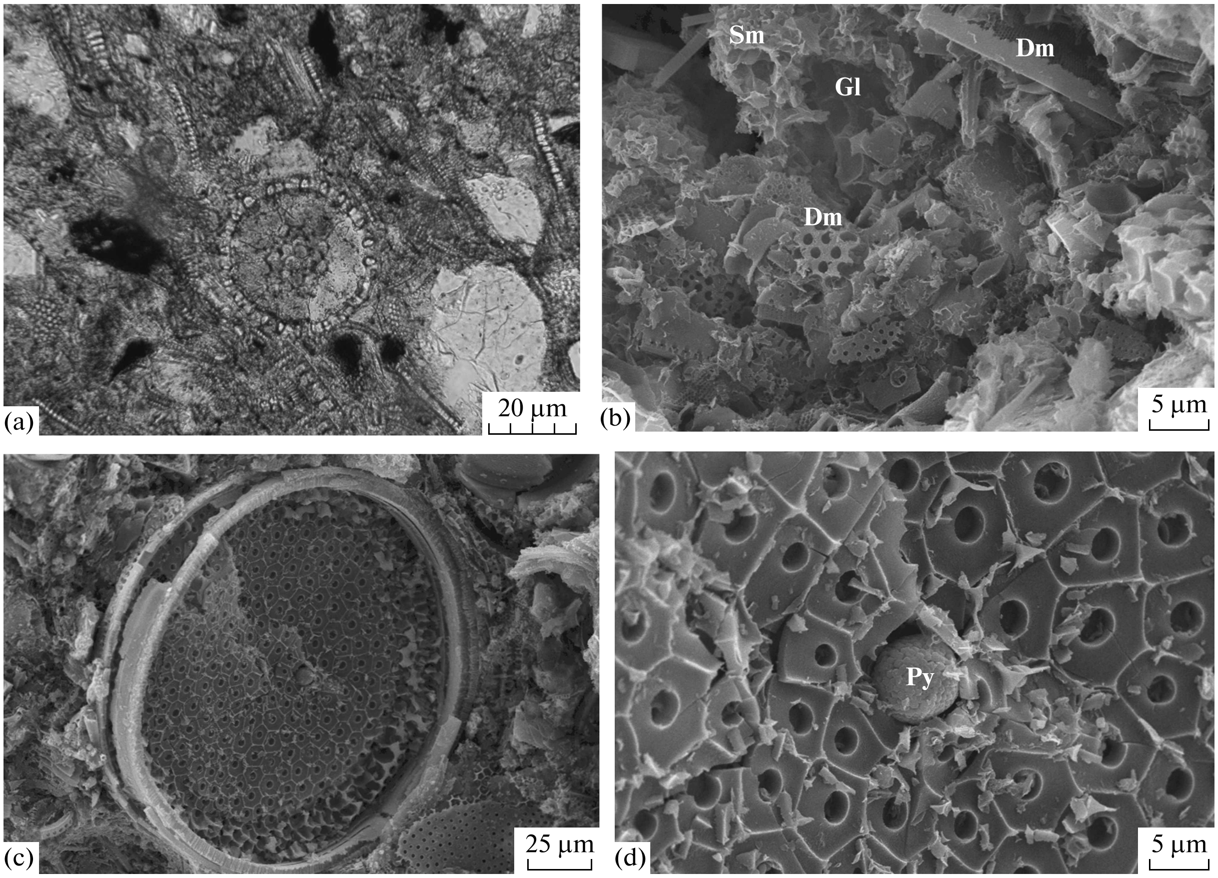

Fig. 3. Tuffites from Cape Okruglyi.
(a) photograph of a polished section. Remains of frustules and radiolarians, H||; (b–d) SEM images: (b) clastic texture of tuffite, (c) frustule, (d) polygonal microstructure of a frustule (at the center is a spherical polycrystalline pyrite aggregate). Sm, smectite; Gl, volcanic glass; Dm, frustule; Py, pyrite.

Mono-opalic rocks are white or light-beige, light, and fine-porous. They widely occur in present-day and probably in older fumarole fields and characterize areas of discharge for acid and ultra-acid hydrothermal fluids with temperatures of approximately 100°C. The main secondary minerals are opal and cristobalite, which nearly completely replace all of the components in the original rock. The minerals that not infrequently associate with opal and cristobalite include jarosite, hematite, and Fe hydroxides, which make the rocks yellow, ocherous, brown, or variegated in color. When seen under an optical microscope, the opalite groundmass does not react to polarized light; low birefringence occurs only in some patches. This is because most of the material is an amorphous or cryptocrystalline condition. The replacement of the original rock is pseudomorphic, with outlines and "shadows" of lithic-crystal clasts. The siliceous matter of frustules that is characteristic for tuffites is dissolved by sulfate leaching and subsequently is precipitated in pores as cristobalite (Figs. 4a, 4b). Judging from the structures that result, leaching and precipitation occur simultaneously. The transformations of mineral compositions and structure of the pore space have completely changed the properties of the original rocks. Opalites are light (1.59–1.81 g/cm^3) and highly porous (25–39%) rocks (Table 2). The low mineral density (2.41–2.67 g/cm^3) is due to the low density of the constituent siliceous a minerals (cristobalite has 2.27 g/cm^3 and opal 1.7–2.5 g/cm^3). Most of the pores (62–85%) are open: they transmit water during free water absorption. Because the siliceous framework is comparatively "stiff" the opalites have relatively high compressional velocities (V_p = 2.9–3.0 km/s) and strength (R_{dry} = 25–46 MPa). Poisson's ratio is low (μ = 0.13–0.14), which is also due to the presence of a stiff porous siliceous framework and is consistent with the fact that fracturing in these rocks is brittle. Water saturation does not affect the strength and elastic properties of the opalites. Ferrugination of opalites increases their density to 2.01–2.09 g/cm^3 owing to a considerable increase in mineral density, up to 2.85–2.96 g/cm^3.

Opal clay rocks are yellowish and the outlines of the original fragments can be seen macroscopically. The main secondary minerals include, apart from siliceous miner-

Table 1. The values of the main indicators of physical and physico-mechanical properties for the Okruglyi tuffites

Sample no.	Density, g/cm^3	Mineral density, g/cm^3	Porosity, %	V_p, km/s	Uniaxial compressive strength, MPa	Strength decrease on saturation with water, %
OK-1	1.21	2.60	54	1.30	4	72
OK-2	1.00	–	–	0.90	–	–
OK-3	1.11	2.58	57	1.30	5	61
OK-4	1.09	2.69	60	1.20	5	66
OK-6	1.48	2.67	44	1.40	3	–
OK-7	1.25	2.62	52	1.50	5	67
OK-8	1.15	2.68	57	1.40	8	65
OK-10	1.30	–	–	1.40	7	69
OK-11	1.23	2.75	55	1.50	5	67
OK-13	1.30	–	–	1.50	5	54
OK-14	1.19	–	–	1.40	8	78
OK-15	1.20	2.68	55	1.50	6	50
OK-16	1.16	2.72	57	1.50	6	53
OK-17	1.26	2.59	51	1.40	6	69
OK-19	1.18	2.69	56	1.50	7	85
OK-20	1.30	2.79	53	0.70	3	Crumbled
OK-21	1.32	2.70	51	1.50	5	71
OK-23	1.30	–	–	1.70	8	78
OK-27	1.11	–	–	1.60	10	55
OK-29	1.20	2.59	53	1.50	8	65

Two dashes mean "not determined."

als, smectites and chlorite in amounts as high as 25%; gypsum and jarosite are also present. These rocks are the most abundant in the area of the North Paramushir hydrothermal magmatic system: they can be seen in bedrock exposures along the Kuz'minka, Matrosskaya, and Gorodskaya rivers, on Mount Mayak, and in the upper part of the tuffite sequence in well GP-3, among other localities. Smectites and chlorite in association with cristobalite replace plagioclase crystal clasts in a pseudomorphic manner (Fig. 5a). The transformations start with defects and microcracks in a crystal, gradually involving all of its volume. The only part that usually remains untouched is the outer crust, which is 5–10 μm thick. This may be due to a zonal structure of crystals, with the marginal zone being more acidic (having an albite composition) and therefore more resistant to the action of thermal water. The cementing mass is composed of colloform cristobalite grains that are covered with a film of clay; the latter acts to create contacts between grains (Fig. 5b). An SEM image clearly shows spheroidal cristobalites 0.1–0.3 μm across that are growing in a pore (Fig. 5c). All around the pore are acicular microcrystals that are 0.2–0.5 nm thick, which probably consist of jarosite. Figure 5d shows a leached plagioclase crystal that has been in part replaced with clay minerals of spongy microtexture, with fibrous acicular jarosite, and with a siliceous material. The marginal shell of the crystal (no thicker than 10 μm) has been preserved. The crystal is surrounded by a dense mass that consists of a siliceous material. The presence of clay minerals increases the porosity in opalites to 41–52% and reduces the values of the physical and mechanical parameters (see Table 2): the compressional velocity was as low as 1.55–1.6 km/s, the modulus of elasticity was 2.9–3.9 GPa, and the compressive strength decreased to 2.8–7 MPa. Fracturing in the rock is now brittle–plastic. When an opal clay rock is saturated with water, its strength is reduced by more than two times, which is related to changes in the properties of clay minerals when moistened, viz., the formation of a layer of osmotic water around clay particles, the occurrence of a wedging-out pressure, and weakening of structural bonds (*Gruntovedenie ...*, 2005).

The *Quartz–alunite rocks* have a massive structure, but contain caverns and large pores due to leaching. These new rocks are also widely abundant in northern Paramushir Island (they have been studied around Lake Izumrudno-Goluboe and in other geological sections along the Vernadskii Range); however, hypsometrically they tend to occur at higher horizons compared with opal clay rocks. The main rock-forming minerals include quartz and alunite, which compose the rock matrix in the form of a dense microcrystalline lepidogranoblastic aggregate (Fig. 6a). Quartz makes microcrystals of xenomorphic sinuous shapes that range between 0.02 and 0.06–0.08 μm across, with some parts of the rock being composed of cryptocrystalline quartz. Alunite is encountered in the form of lamellate anisometric crystals 2–10 μm thick (Figs. 6b, 6c) that are found in the interclastic space and between quartz crystals. X-ray phase analysis was used to find that the concentration of alunite in the rock varies between 6–7 and 43%. Tridymite is generated on the surface of quartz and alunite crystals and on preserved plagioclase remains. The tridymite is found in the form of trillings or rosette-shaped microaggregates that consist of pseudo-hexagonal lamellate crystals 0.2–0.5 μm across (Fig. 6d). The degree of reworking of the original rocks is high, tuffites and tuffs being nearly completely recrystallized to become quartz–alunite aggregates, but the original texture can be identified from pseudomorph replacements. The quartz–alunite metasomatites are dense (ρ = 2.29–2.32 g/cm^3), non-hygroscopic rocks. The morphology of the pore space in the original rocks varied under the action of differently directed hydrothermal processes: first, the fragment matrix was completely recrystallized to become a dense lepidogranoblastic, quartz–alunite microaggregate, resulting in the disappearance of the original porosity; secondly, leaching by thermal water led to the formation of secondary pores of the size of large caverns. As a result, the average porosity of quartz–alunite rocks is 16–17%. However, the open porosity does not exceed 6–7%, thus indicating the prevalence of isolated pores that are impermeable to water. Compressional velocities are high (V_p = 4.45–5.0 km/s), owing to the high rock density. The quartz–alunite rocks have a high compressive strength that varies in the range between 43 and 104 MPa. One notes a considerable difference in strength for closely lying values of density and porosity. This seems to be related to differences, first, in the quantitative concentrations of quartz and alunite and, secondly, in the features of microstructure that are peculiar to these rocks. The rocks that have the highest strength are those in which alunite has replaced plagioclase crystal clasts and individual lithoclasts, being inside a strongly cemented quartz microaggregate that makes up a stiff framework; the concentration of alunite is 6–7%. Increased alunite concentrations (up to 42%), the generation of alunite in the form of nest-shaped accumulations in the groundmass or in the interclastic space (see Fig. 6b), the presence of alunite plates on the contacts between quartz grains, and weak contacts between grains in the basis–fracture type (see Fig. 6c) all reduce the rock strength by more than two times. Saturation with water leaves the strength of quartz–alunite rocks practically unaffected, their coefficient of softening is 0.91–0.96. The character of fracture when under loading is brittle.

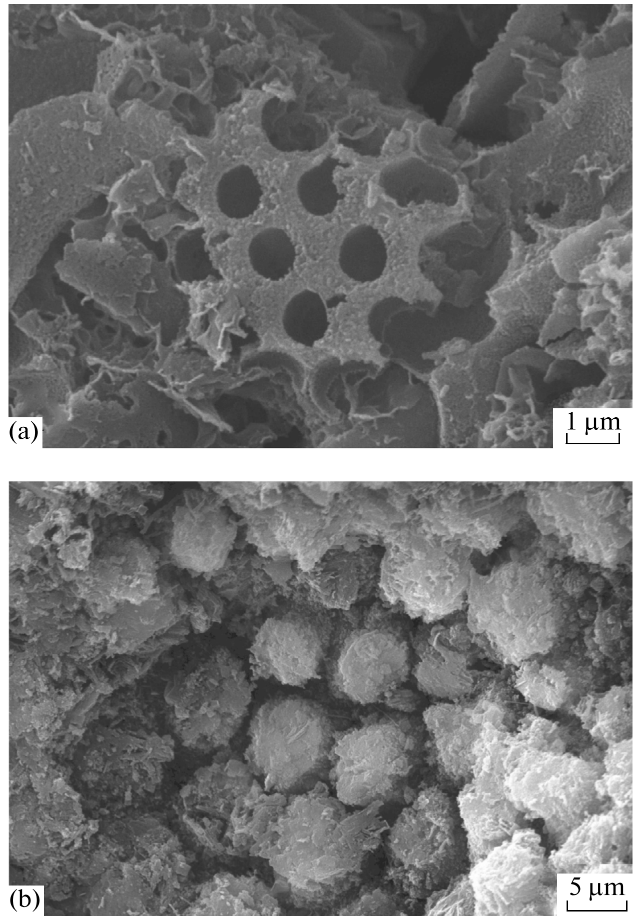

Fig. 4. The recrystallization of a frustule into cristobalite by the action of thermal water. SEM images.
(a) unaltered shell (Okruglyi tuffite), (b) shell when replaced with cristobalite (opalite, Gorodskaya R.).

The opalite rock sequence has a zonal structure as a whole. The most prevalent opal clay rocks are generated by filtration of neutral or weakly acidic hydrocarbonate sulfate solutions along highly porous and fissured tuffites and tuffs. The quartz–alunite rocks make an "overstructure" above the upper horizons of opal clay rocks and are probably formed in the zone of condensation of acidic steam–gas fluids (in the region where secondary sulfate waters are generated). Mono-opal rocks more frequently mark the locations where acidic and ultra-acidic thermal waters are discharged. The waters tend to concentrate in the near-summit part of the Vernadskii Range or in individual present-day and former volcanic centers. They develop on volcanic rocks as well, in addition to volcanogenic sedimentary rocks. The rocks in each zone have their own distinguishing physical and mechanical properties and play a certain part in the hydrothermal magmatic system.

Table 2. The values of the main indicators of physical and physico-mechanical properties for opalites

Sampling site	Sample no.	Density, g/cm^3	Mineral density, g/cm^3	Porosity, %	V_p, km/s	Modulus of elasticity, GPa	Uniaxial compressive strength, MPa	Strength decrease on saturation with water
Mono-opalites								
Gorodskaya R	2/712	1.59	2.41	34	3.0	–	28	–
	Eb-8/10-1	1.81	2.41	25	2.9	15	25	0
	Eb-9/10-1	1.64	2.67	39	3.0	14	46	0
Ferrous mono-opalites								
Kuz'minka R, Lake Izumrudno-Goluboe	2/717	2.09	2.85	27	3.4	–	40	28
	Eb-27/10-1	2.01	2.96	17	3.4	19	28	34
Opal–clayey rocks								
Gorodskaya R	Eb-11/10	1.64	2.76	41	1.6	3.9	7	67
Lake Izumrudno-Goluboe	Eb-19/10-3	1.34	2.75	52	1.55	2.9	2.8	–
Quartz–alunite rocks								
Lake Izumrudno-Goluboe	Eb-27-10/3a	2.32	2.80	17	4.45	43	43	9
	Eb-27-10/3b	2.29	2.72	16	5.05	36	104	4

LOW-TEMPERATURE PROPYLITES

These rocks were studied in wells P-1, P-3, P-4, and P-5, as well as in natural exposures on Mount Mayak. They were formed by hydrothermal metasomatic alteration that affects lithocrystalline and vitrocrystalline clastic tuffs and tuffites with aleurite and psammite textures. The degree of alteration varies. It can be seen in low-alteration samples that the original rocks were similar to the Okruglyi tuffites. These too contain the remains of frustules and glauconite grains, an incipient process of recrystallization affects diatom remains to replace them with smectites and siliceous minerals. The alteration is seen as new minerals being generated, viz., albite, quartz, calcite, zeolite (heulandite and desmine), chlorite, and smectite, with hydromica and kaolinite being less abundant. There are ore minerals such as pyrite and ilmenite, with the latter replacing titanomagnetite.

The cement in the propylites is fine-dispersed and microporous (pores of 1–5 microns), it is polymineral and has an inhomogeneous structure. This can with difficulty be detected under an optical microscope. Inspection using an electron microscope showed that the rocks contain microcrystals of feldspar, quartz, chlorite, and smectite. The quantitative concentrations of these components strongly vary among different parts of a rock; for example, the groundmass may consist of a microcrystalline feldspar aggregate (the crystals are 1–2 to 10–20 μm long and 1–5 μm wide), siliceous clay material with a scaly acicular microtexture, microporous feldspar clay aggregate that includes scaly fibrous clay mineral, and feldspar crystals 1–5 μm across. It can also be seen in polished sections that the rock is cemented with a carbonate material in some patches. The cement in the low-temperature propylites may thus be very inhomogeneous, even within a single sample.

Plagioclase crystals experience intensive leaching and albitization. The replacement of plagioclase with albite starts with defects, microcracks, and inclusions of volcanic glass, which gradually involve all of the crystal. Similarly to the situation in the zone of sulfate leaching, the crystal edges frequently preserve the original shape and composition. Zeolite (heulandite) is occasionally encountered in association with albite. Some plagioclase crystals are replaced with calcite in a pseudomorphic manner. The crystal clasts of pyroxene and hornblende are nearly unaltered. Some samples contain thin veins filled with calcite and quartz.

The low-temperature propylites have higher values of the parameters of their physical and mechanical properties compared with unaltered tuffites (Table 3). Propylitization leads to considerable compaction, occasionally reaching density values of 1.86–2.27 g/cm^3, while the mineral density is only slightly increased. The porosity is two times lower with accompanying reduction in the percentage of open pores. Rock compaction naturally leads to higher compression velocities, up to 2.05–3.4 km/s. Saturation with water usually reduces the velocity, but a reverse effect is occasionally observed. The values of V_p are reduced by saturation owing to an admixture of clay minerals, with the contacts between these being weakened in

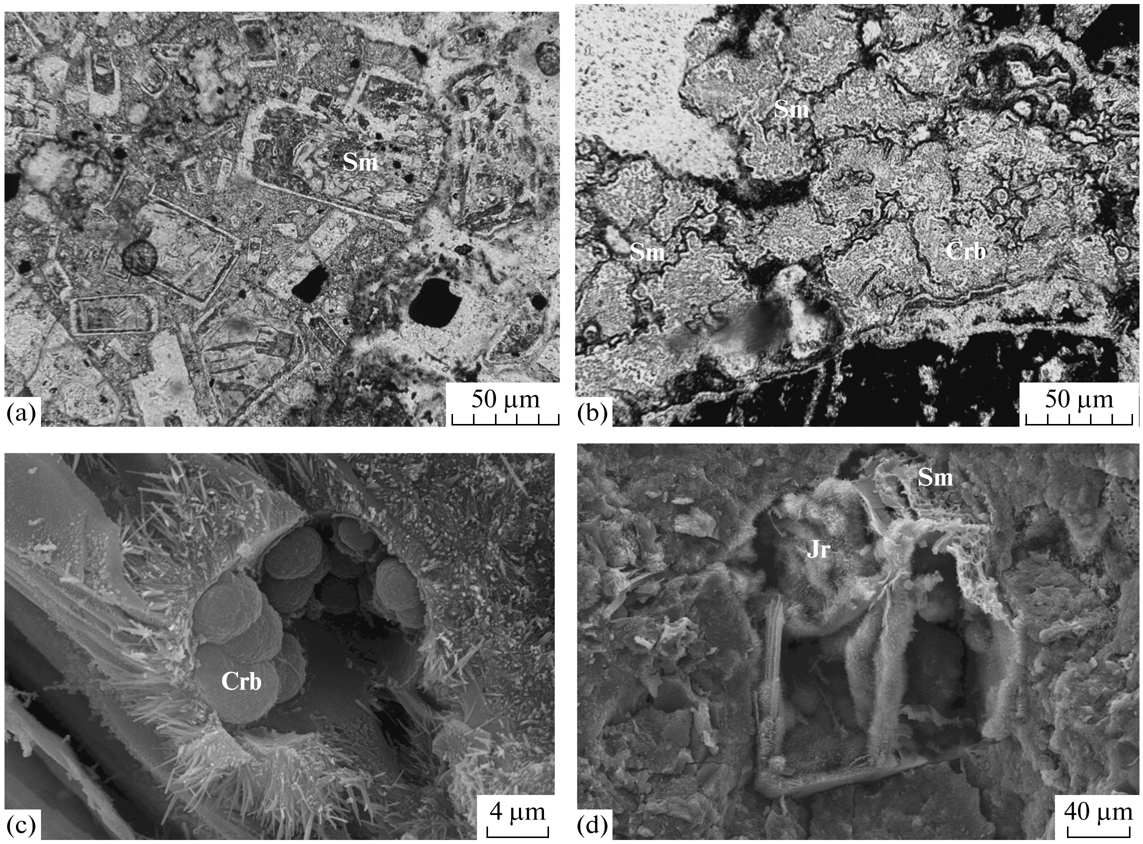

Fig. 5. The structure of opal–clayey rocks.
(a, b) photographs of polished sections: (a) pseudomorphic replacement of plagioclase crystals with cristobalite and clay minerals; (b) cementing mass: colloform formations of cristobalite with films of clay minerals, H||; (c, d) SEM images: (c) spheroidal formations of cristobalite in a pore; (d) leached plagioclase crystal that has been partially replaced with jarosite and a clay mineral, the crystal being surrounded with a siliceous material. Sm, smectite; Crb, cristobalite; Jr jarosite.

water; this leads to slower compressional waves. The increase in V_p due to water saturation occurs in the absence of minimal concentrations of clay material due to the filling of the pore and fissure space with water in which compressional waves are known to have higher velocities than in air. The uniaxial compressive strength varies in a wide range, between 14 and 64 MPa. This scatter is due to inhomogeneities in the composition and structure of the cementing mass, as was shown above. Overall, the low-temperature propylites have much greater strength compared with unaltered tuffites and tuffs.

MODERATE-TEMPERATURE PROPYLITES

These rocks were reached at depths of 1300–2500 m by well GP-3. They were generated from lithic-crystal clastic tuffs and intrusive breccias under the action of high-temperature (>150°C) thermal water. The rock-forming minerals are mostly quartz (25–55%), albite (20–50%), and sericite; as well, there are chlorite (up to 10–20%), epidote, calcite, adularia, dickite, zeolites, prehnite, anhydrite, pyrite, and rutile. This zone is remarkable in that the original rocks have been completely recrystallized. The hydrothermal metasomatic alteration consists in the replacement of cement in tuffs with a crypto- and micro-crystalline, granoblastic, quartz or quartz–feldspar–sericite–chlorite aggregate in association with dickite or quartz–feldspar–sericite–chlorite micrograin material. The lithic clasts are subject to identical transformations. Crystal clasts of plagioclase are replaced, with albite, sericite, and dickite being developed on these in a pseudomorphic manner, as well as with accumulations of epidote grains. One also encounters leached plagioclase crystals. The pyroxene has been completely leached and replaced with epidote, quartz, chlorite, and ore minerals. The hydrothermal metasomatism was so intense that it completely altered the original clastic texture of tuffs and breccias, transforming these into quartz–sericite, quartz–albite–sericite–chlorite metasomatites with secondary texture. The pores of moderate-temperature propylites are filled with the same material as the groundmass. The fissures that cut across the rock are filled with mosaic quartz whose crystals reach 0.1–0.2 mm across. The ore minerals include pyrite, rutile,

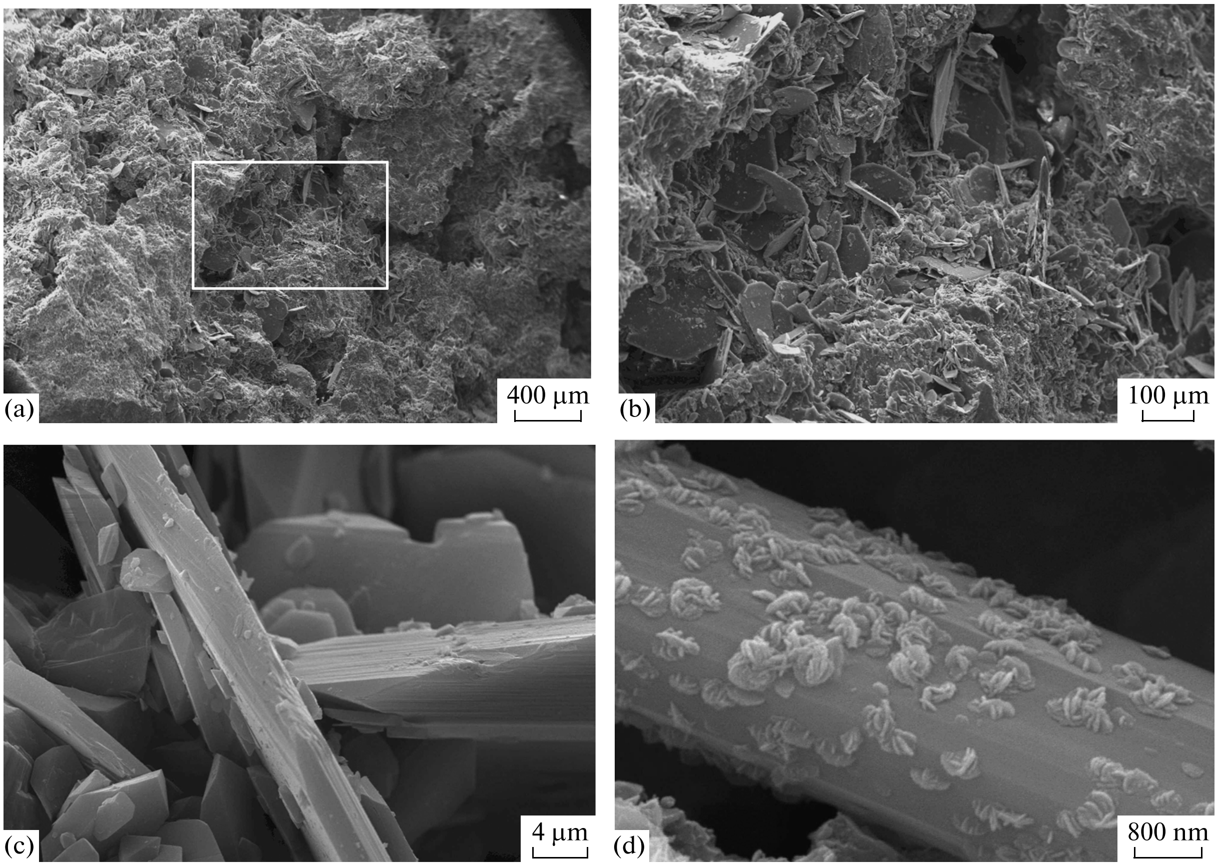

Fig. 6. The structure of quartz–alunite metasomatites. SEM images.
(a) dense cryptocrystalline quartz–alunite aggregate: quartz becomes surrounded by debris, alunite develops in interdebris space; (b) patch that is composed of lamellar alunite crystals; (c) contact between alunite lamellae in the basis–fracture type; (d) rosette-shaped tridymite aggregates that grow on the surface of a plagioclase crystal.

and titanomagnetite. A pyrite crystal was found to contain inclusions of titanomagnetite and original plagioclase. The plagioclase seems to have been captured and preserved during the growth of the pyrite crystal.

Moderate-temperature propylites have the strongest contacts between newly formed crystals. The original breccia porosity disappears in them due to a high degree of alteration of the original rocks. It is because of this that they have the highest physical and mechanical parameters (Table 4). The propylites have densities of 2.49–2.64 g/cm^3 and mineral densities in the range 2.73–2.93 g/cm^3, which is due to the presence of heavy Fe and Mg bearing minerals (oxides, epidote, and chlorite). The rocks are not hygroscopic, which is only natural, since hygroscopic water is characteristic for clay minerals that are not generated at these temperatures. The porosity varies within the 6–14% range. The quartz grains form a dense aggregate (Fig. 7a). However, when seen at high magnification, the space between the quartz grains was found to be composed of cericite (Fig. 7b), chlorite, and dickite. It contains micropores that are a few microns across. The density increases and porosity decreases with increasing depth. As well, the percentage of open pores is reduced, that is, the permeability is diminished. The moderate-temperature propylites typically have high elasticity parameters; for example, compression velocities vary between 3.6 and 4.4 km/s, increasing to reach 4.2–4.5 km/s when the rock is saturated with water. The uniaxial compressive strength is high, ranging between 49 and 133 MPa. The high strength of the rocks is due to rigid structural bonds in the micrograin quartz or quartz–feldspar aggregate that is formed by hydrothermal metamorphism of the original tuff and breccia. The wide scatter of strength values is due to non-uniform alteration of the rocks and variability in compositions and microstructure of the secondary cement, with the cement containing, in addition to quartz and feldspar, chlorite, sericite, and dickite, whose aggregates have a porous microstructure; this naturally reduces the strength. The moderate-temperature propylites are stable under water saturation; their strength either remains unaffected in water or decreases only slightly.

Table 3. The values of physico-mechanical parameters peculiar to low-temperature propylites

Sampling site	Sample no. (in wells; sampling depth is in m)	Density, g/cm^3	Mineral density, g/cm^3	Porosity, %	V_p, km/s	Uniaxial compressive strength, MPa
Well P-1	29	2.12	2.84	25	2.45	17
Well P-1	37.5	2.19	2.83	23	2.80	29
Well P-1	46.5	2.18	2.86	24	2.20	30
Well P-3	36.3	2.14	2.78	23	3.20	43
Well P-3	38	2.00	2.77	28	2.30	20
Well P-3	40.5	2.03	2.75	26	2.30	25
Well P-4	9	2.13	2.75	23	2.45	29
Well P-4	11.5	2.08	2.82	26	2.35	32
Well P-4	14	2.16	2.82	23	2.30	30
Well P-4	18.5	2.00	2.72	26	2.70	46
Well P-5	5.8	1.92	2.74	30	2.25	22
Well P-5	8.5	1.87	2.71	31	2.05	15
Well P-5	9.8	2.12	2.73	22	–	64
Well P-5	10.8	1.99	2.72	27	2.00	22
Well P-5	13	1.97	2.67	26	3.05	20
Well P-5	13	2.15	2.67	19	2.95	59
Well P-5	13	1.86	2.67	30	2.10	14
Well P-5	14.5	1.95	2.74	29	2.20	17
Well P-5	17.5	2.27	2.68	15	3.40	–
Mayak Mt	3/47-a	2.04	2.60	22	3.10	45
Mayak Mt	3/47-b	2.12	2.60	18	3.40	–

Table 4. The values of physical and physico-mechanical parameters for moderate-temperature propylites

Sampling site	Sampling depth	Density, g/cm^3	Mineral density, g/cm^3	Porosity, %	V_p, km/s	Uniaxial compressive strength, MPa	Strength decrease on saturation with water, %
Well GP-3	1307	2.49	2.73	9	3.90	116	–
	1308	2.49	2.74	9	4.10	133	2
	1310	2.51	2.93	14	3.60	120	–
	1446	2.59	2.91	11	–	–	–
	1646	2.58	2.79	8	4.40	96	2
	2004	2.64	2.81	6	4.10	49	29

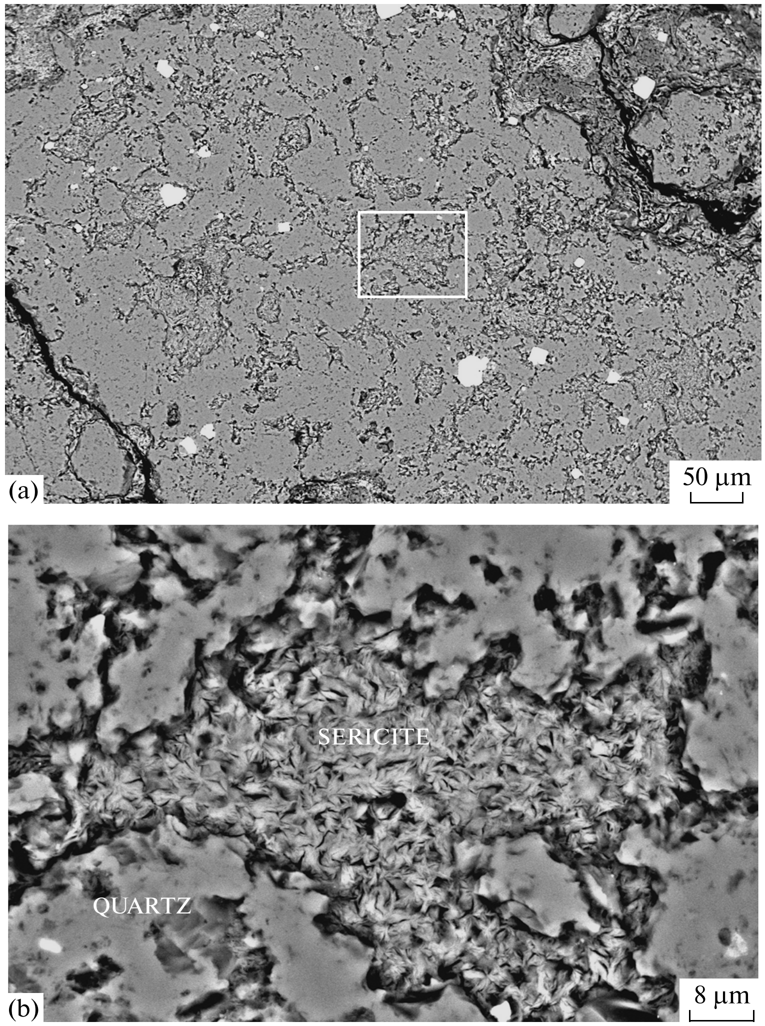

Fig. 7. Microtexture of moderate-temperature propylite (well GP-3, depth 1300 m). SEM image.
(a) quartz–sericite microaggregate, (b) same under increased magnification.

PATTERNS IN THE VARIATION OF ROCK PROPERTIES

Volcanogenic sedimentary rocks make a thick mass in the structure of the North Paramushir hydrothermal magmatic system and play an important part in the distribution of flows of hydrothermal fluids and meteoric (mixed) water. It was essential for the study of the patterns that govern the variation of rock properties in the structure of the system that one identify the original rocks, i.e., those that are unaffected by hydrothermal metasomatism. Volcanogenic sedimentary rocks of this type (mostly tuffites) were studied in the Cape Okruglyi section (see Figs. 1, 2). As pointed out above, these rocks have high open microporosity and microfissuring and poor cementation of clastic material; they contain great amounts of easily decomposable volcanic glass and silica. These properties of the rocks controlled the direction and intensity of their alteration by hydrothermal metasomatism.

Tuffites and tuffs (and seemingly lavas of andesites and basaltic andesites as well) are converted into monoopalites in the centers of the discharge of acidic and ultraacidic chloride sulfate water (in present-day and older thermal fields) in the upper horizons of the hydrothermal magmatic system. The original material is being recrystallized (in many cases completely) into various low-temperature polymorphic modifications of silica such as opal, cristobalite, tridymite, and quartz. On the one hand, intensive replacement and leaching is affecting the secondary components, producing cavities, while on the other hand, secondary minerals are generated in the pores. The volume of newly generated material exceeded that of the leached material, judging from the total diminution of the rock porosity (by 50–60% in tuffites and 25–40% for opalites). Recrystallization and the formation of a rigid siliceous framework considerably enhance the elastic properties and strength, in spite of the low density of opalites (Figs. 8a, 8b and Table 5); for example, the strength is increased by opalitization by an average of 5–6 and is not diminished by water saturation, unlike in the case of unaltered rocks. The admixtures of ferrous hydroxides that are characteristic for mono-opalites tend to considerably increase the strength of the rock, but do not appreciably affect its mechanical properties.

At deeper horizons in the hydrothermal magmatic system tuffites and tuffs are transformed into opal–clay rocks due to active circulation of neutral and alkaline chloride–sodium and hydrocarbonate thermal waters. The presence of clay minerals (up to 25 vol %) appreciably reduces the elasticity and strength parameters of the rocks and makes them vulnerable to the actions of water. The properties of newly generated rocks are also substantially affected by how the clay minerals are liberated. When clay fills the pore space inside a siliceous matrix or replaces plagioclase crystals, this appreciably enhances the hygroscopic humidity (Fig. 9a), but does not produce large changes in physical and mechanical properties. Strength and elasticity parameters are substantially diminished only when the clay minerals form thin films around cristobalite crystals that compose the cementing mass (see above). This reduces the contact strength, especially when the rock is saturated with water, because clay minerals (smectites in the case under consideration) contain osmotic water, which exerts a wedging-out effect on the clay particles and weakens the structural bonds. Overall, the argillization of tuffites and tuffs enhances their permeability to water, in spite of the high total porosity (41–52%). This occurs due to the fact that the pores are very small and are completely filled with water on moistening. Water is adsorbed on the surface of clay particles, hampering free filtration of solutions through the rock.

Quartz–alunite metasomatites are the rocks that have the highest density and strength and are the least subject to deformation in the opalite series. The rocks are not hygroscopic and are stable under the action of water. This property is due to a wide abundance of microcrystalline cement that consists of strongly coalesced grains of secondary quartz. The presence of alunite at grain boundaries weakens the contacts and generally reduces the strength of this rock. Based on the composition, properties, and position of quartz–alunite metasomatites in the structure of the hydrothermal magmatic system, we believe that the metasomatites were formed by filtration of acidic sulfate waters through original rocks in the zone of condensation of the steam–gas fluid (above large regions of boiling hydrothermal fluids). Such zones are widely abundant along the axial part of the Vernadskii Range and can act as an additional (secondary) aquifuge and a heat-shielding horizon in the structure of the hydrothermal magmatic system.

The propylitization of tuffs and tuffites makes them denser, stronger, more porous, and enhances their elastic characteristics. The moderate-temperature propylites have substantially higher values of elasticity, density, and strength parameters compared with the low-temperature propylites; for example, porosity (50–60%) is reduced by an average of two times as a consequence of low-temperature propylitization, and by five times as a result of moderate-temperature propylitization, with a concomitant decrease in the percentage of open pores. The density is increased from 1.22 g/cm^3 to 2.06 and 2.55 g/cm^3, the strength increases from 6 MPa to 30 and 100 MPa, and the compressional velocity V_P increases from 1.4 km/s to 2.6 and 4.0 km/s, respectively. The hygroscopic humidity of tuff and tuffite is increased during low-temperature propylitization, occasionally reaching 3.7% (this is due to a high concentration of clay minerals), but practically vanishes during moderate-temperature transformations. Thus, dense rocks of high strength resulted from originally porous and low-strength volcanogenic sedimentary rocks by hydrothermal metasomatic alteration. The greatest changes in rock properties were produced through high-temperature chloride–sodium solutions: a thin fine-clastic groundmass has been completely recrystallized to become a dense microcrystalline aggregate with strong intergranular contacts, while the original debris porosity has nearly disappeared because the voids have been filled with secondary minerals (quartz, albite, muscovite, chlorite, and epidote). A great contribution to this compaction and strengthening is due to secondary quartz, which forms a microcrystalline aggregate that consists of strongly coalesced grains with sinuous xenomorphic outlines of the surface. The plots in Figs. 9b, 9c, and 9d show how the concentration of quartz affects rock properties, viz., increasing the density, compressional velocity, and strength. These parameters increased as the concentration of quartz increased to approximately 50%. This was followed by stabilization, that is, the properties reached their highest values. The presence of other secondary minerals in the intergranular space does not affect the strength and elasticity properties significantly, so far as these minerals are within the quartz aggregate. However, the strength dramatically decreased when other secondary minerals filled the space between quartz grains or made up entire regions in the rock. As hydrothermal metasomatic transformations continue, the result is to decrease, not only total porosity, but also the percentage of open pores that can filter water. In the moderate-temperature propylites this is due to the generation of a dense microcrystalline aggregate that consists of strongly coalesced grains of minerals (mostly quartz). In the low-temperature propylites and in opal–clay rocks this is caused by a wide abundance of hydrothermal clay minerals: the large number of water-filled micropores that is typical of such formations impedes the filtering of hydrothermal brine.

It should be noted that the variation of physical and mechanical properties in relation to density and porosity are described by several common trends for unaltered

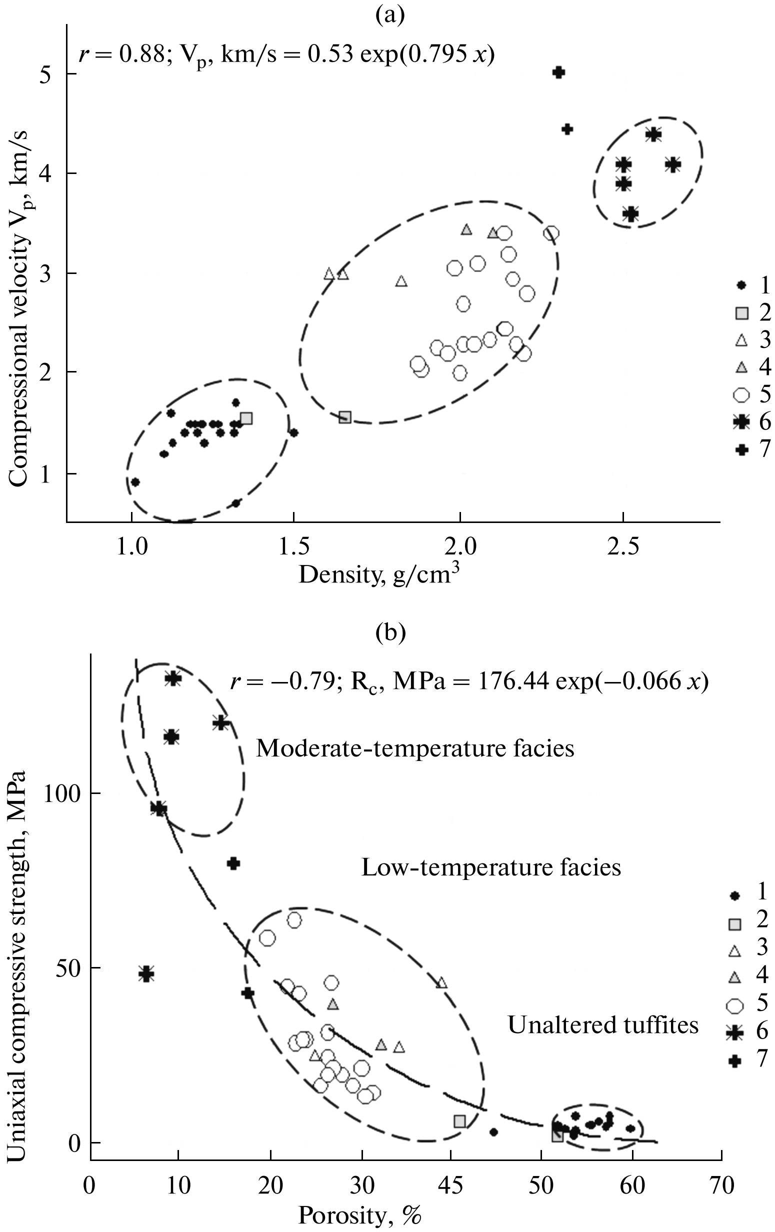

Fig. 8. Plots showing the compressional velocity versus density (a) and uniaxial compressive strength (b) for different rocks. (1) unaltered tuffites, (2) opal claystone, (3) mono-opalites, (4) ferrous mono-opalites, (5) low-temperature propylites, (6) moderate-temperature propylites, (7) quartz–alunite metasomatites.

tuffs and tuffites and for the rocks of all hydrothermal facies (see Fig. 8); for example, the variation of the compressional velocity in relation to the density is characterized by a close correlative relationship ($r = 0.88$) and is described by an exponential equation. Compressive strength and porosity is also connected with a close correlative relationship ($r = -0.79$) and an inverse exponential relationship. Although each of the hydrothermal facies in the diagram concentrates in a definite region, this nevertheless occurs within a single trend. This may indicate a common origin (a common source and a definite direction) of hydrothermal metasomatic processes that occur in the interior of the North Paramushir system. This hypothesis is consistent with an earlier inference, viz., that the system is at a progressive phase of evolution (Rychagov et al., 2002). A regressive phase of evolution in a system typically has low-temperature transformations superposed upon high-temperature transformations; as a result, the relationship between the properties of newly generated rocks is violated. This was, in particular, shown for the Pauzhetka hydrothermal system (Frolova et al., 2011).

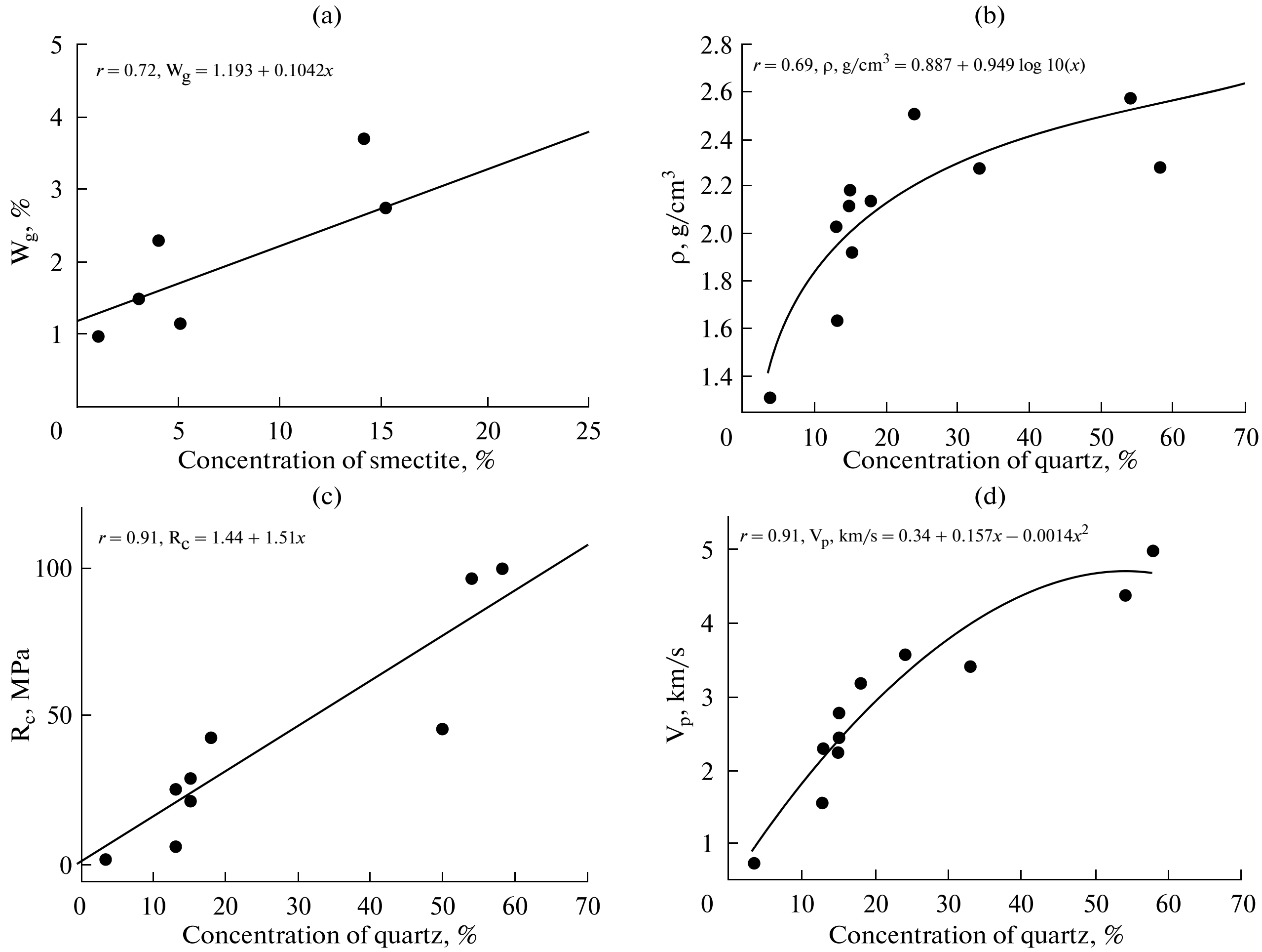

Fig. 9. The concentrations of secondary minerals as affecting the properties of hydrothermal metasomatic rocks. (a) hygroscopic humidity (W_g) versus the concentration of smectites; (b) density (ρ) as a function of quartz concentration; (c) uniaxial compressive strength (R_c) as a function of quartz concentration; (d) compressional velocity (V_p) as a function of quartz concentration.

CONCLUSIONS

(1) Considering the series of unaltered tuffs and tuffites to low-temperature hydrothermal metasomatic facies to moderate-temperature facies, we see decreasing rock density, compaction, strengthening, and increasing elasticity characteristics. The greatest changes in properties are caused by deep-seated high-temperature alkaline and neutral chloride–sodium solutions that recrystallize the porous fine-clastic, poorly cemented groundmass of the original rocks into a dense microcrystalline granoblastic quartz or feldspar–quartz aggregate with strong contacts between the constituent grains. The original porosity is lost because the voids are filled with secondary minerals, with the prevailing minerals being quartz, albite, chlorite, sericite, epidote, and dickite.

(2) Hydrothermal metasomatic alteration in original rocks diminishes the percentage of open pores and microcracks that can filter hydrothermal brines. The deposition of secondary minerals (primarily siliceous and clay minerals) creates favorable conditions for the isolation of flows of hydrothermal fluids and for the formation of additional (secondary) heat-insulating and aquifuge horizons. The process is probably more frequent in the upper parts of major hydrothermal boiling zones where acidic sulfate waters are condensed.

(3) The relationships among the properties of unaltered volcanogenic sedimentary rocks, opalites, low- and moderate-temperature propylites obey a common trend, which may indicate the generation of hydrothermal metasomatic rocks in the course of the unidirectional process during the progressive phase in the evolution of the North Paramushir hydrothermal magmatic system. This inference is consistent with our earlier geological–structural, mineralogic and geochemical data.

(4) Since hydrothermal metasomatic alteration leads to a persistent decrease in rock porosity (by factors of 5–6), and the volume of newly generated material consider-

Table 5. A review table showing parameters of physical and physico-mechanical properties for unaltered tuffites and hydrothermally altered rocks in the North Paramushir hydrothermal magmatic system

Rock		ρ, g/cm^3	ρ_s, g/cm^3	n, %	n_o, %	n_o/n	V_p, km/s	V_{pw}, km/s	R_c, MPa	K_{soft}, arb.u	$\chi \times 10^{-3}$ CI	Number of samples	Secondary minerals
Unaltered tuffites		1.0–1.48 / 1.22	2.58–2.79 / 2.67	44–61 / 54	36–55 / 46	0.71–0.92 / 0.87	0.7–1.7 / 1.4	0.6–1.7 / 1.3	3–10 / 5.9	0.15–0.5 / 0.32	0.52	20	Cristobalite, smectites, hydromica (in small amounts)
Opaline	Opal—clay rocks	1.34–1.64 / 1.49	2.76	41–52 / 46	24–42 / 33	0.59–0.81 / 0.70	1.5–1.6 / 1.55	–	2.8–7 / 4.7	0.43	17	2	Clay minerals, opal, cristobalite, gypsum
Opaline	Mono-opalites	1.59–1.81 / 1.68	2.41–2.67 / 2.50	25–39 / 32	15–29 / 23	0.62–0.84 / 0.69	2.9–3.0 / 3.0	2.61–3.0 / 2.9	25–46 / 33	1	0.22	3	Opal, cristobalite
Opaline	Opalites + Fe	2.01–2.09 / 2.05	2.85–2.96 / 2.90	27–32 / 29	17–19 / 18	0.53–0.73 / 0.63	3.40	2.9–3.3 / 3.1	28–40 / 34	0.67–0.72 / 0.70	–	2	Opal, cristobalite, chalcedony, hydroxides, Fe, jarosite
Opaline	Quartz—alunite rocks	2.29–2.32 / 2.30	2.72–2.80 / 2.76	16–17 / 16.5	6.2	0.42	4.45–5.0 / 4.75	3.78–5.0 / 3.8	43–104 / 73	0.8–0.9 / 0.85	–	2	Quartz, alunite
Low temperature propylites		1.86–2.27 / 2.06	2.6–2.86 / 2.74	15–31 / 25	10–23 / 17	0.55–0.78 / 0.66	2.05–3.4 / 2.6	1.6–3.3 / 2.4	14–64 / 30	–	2.3–29.5 / 18	22	Smectites, hydromica, chlorite, quartz, albite, calcite, zeolites
Medium temperature propylites		2.49–2.64 / 2.55	2.73–2.93 / 2.82	6–14 / 9.5	0.3–6.5 / 4.3	0.04–0.74 / 0.50	3.6–4.4 / 4.0	4.2–4.5 / 4.35	49–197 / 103	0.71–1.0 / 0.90	0.01–0.15 / 0.05	6	Quartz, albite, muscovite, epidote, adularia, zeolites, prenite, chlorite, dickite, ore minerals

The least and greatest values of a parameter are above the line, the mean is below the line.

ably exceeds that of the leached original material, the material is typically transported from lower horizons of the system during the progressive phase of the hydrothermal magmatic system.

ACKNOWLEDGMENTS

We express deep gratitude to all of our colleagues who took part in the field work, and to workers at the analytical services of the Department of Geology, Moscow State University and the Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences for extensive laboratory studies. This work was supported by the Russian Foundation for Basic Research (project nos. 13-05-00530, 13-05-00262, and 14-05-00708).

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Translated by A. Petrosyan