Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

Argillization and its influence on physical and mechanical properties of andesites on the Eastern-Pauzhetsky thermal field, Kamchatka Peninsula

Bolshakov Ilya[1], Frolova Julia[1], Chernov Michael[1], Mosin Alexey[1] and Rychagov Sergey[2]

[1]Faculty of Geology, Lomonosov Moscow State University, Leninskiye Gory 1, GSP-1, Moscow 119234, Russia

[2]Institute of Volcanology and Seismology, Far East Branch, Russian Academy of Sciences, 9 Piipa Avenue, Petropavlovsk-Kamchatskii, 683006 Russia

bolshakov.ilya.210@yandex.ru

Keywords: thermal field, Kamchatka, hydrothermal argillization, secondary minerals, physical-mechanical properties

ABSTRACT

The Pauzhetsky hydrothermal system is located on the South Kamchatka (Far East, Russia) and is used for electricity production. Due to the discharge of thermal water and steam, several thermal fields were formed on the surface. The object of present research is the Eastern-Pauzhetsky field. This field is characterized by the natural regime of steam and thermal waters discharge, since it is located at a distance from production wells. The field was studied with boreholes and open pits down to the depth 7-8 m. It is formed in andesites, which are dense, low porous rocks with high strength. Due to the action of thermal water, the andesites are argillized with developing of smectites and high-silica zeolites. Hydrothermal argillization of andesites causes their decompression and leaching, an increase in porosity, while their elastic and strength properties are significantly reduced. This trend in changing properties contributes to further progressive argillization. Upwards along the section, andesites transform to metasomatic breccia consisting of andesite fragments cemented with secondary minerals (smectites, zeolites, opal, quartz, calcite, and pyrite). The maximum alteration of initial andesites is achieved in the near-surface horizon where they totally transform to hydrothermal clays forming insulating "cover" above the field. Clay horizon has a zonal structure, which is expressed in a change in color, texture, grain size, mineral composition, consistency, and properties of soils. In particular, smectites prevail in the lower part of the clayey horizon, while kaolinite in the upper part. Thus, three horizons are distinguished along the section: argillized andesites, metasomatic breccia, and hydrothermal clays.

1. INTRODUCTION

With the passage of time and an increase in the pace of technological development, mankind is becoming increasingly interested in using unconventional sources of heat and electricity. An excellent example of such sources is the energy of the Earth, which is called geothermal energy. The world community is actively pursuing the study of hydrothermal systems and related deposits of thermal waters and steam. These deposits serve as excellent sources of electric and thermal energy. One of the main advantages of geothermal sources is their minimal negative impact on the environment and their renewability. Also, hydrothermal systems can serve as sources of various minerals.

The first geothermal power plant in the USSR was the Pauzhetskaya power station, located in the south of the Kamchatka Peninsula in the valley of the Pauzhetka river. The Pauzhetskaya GeoPP, commissioned in 1966, has a capacity of 5 MW_e and provides electricity to over 2000 people in one of the furthest remote corners of Russia. This power plant uses superheated dry steam from the Pauzhetskoye deposit of thermal water from depths of more than 600 m.

Due to the discharge of thermal water and steam, several thermal fields with multiple thermal manifestations were formed on the surface. The object of present research is the Eastern-Pauzhetsky field. This field is characterized by the natural regime of steam and thermal water discharge, since it is located at a distance from production wells.

The hydrothermal process is often associated with rock alterations, including the transformation of their composition and a change in properties. The altered rocks of the Pauzhetsky geothermal area are of interest to engineering geology, since they serve as bases for constructions of geothermal power stations and pipelines transporting superheated steam from the wells to the station. In addition, these rocks are very poorly studied, as well as their physical and mechanical properties. The most intense changes in rocks occur within thermal fields. First of all, it is the argillization of rocks, which consists in the development of clay minerals.

The argillic zone is well-studied with respect to mineralogy, but the changes in rock physical-mechanical properties due to argillization are generally poorly characterized. Nevertheless, the engineering geological study of hydrothermal argillization is of great importance. Hydrothermal clays, forming the upper part of the thermal fields affect the selection of sites for power plant constructions. Many researches have noted that clay minerals significantly weaken initial rocks and decrease their mechanical properties (Frolova et al., 2006; Potro and Hürlimann, 2009; Pola et al., 2012; Siratovich et al., 2012; Mielke et al., 2015; Navelot et al., 2016).

The purpose of this research is to study the alteration of volcanic rocks and changes in their physical-mechanical properties under the action of hydrothermal argillization on the East Pauzhetsky thermal field.

2. GEOLOGICAL SETTING

2.1 Characterization of the Pauzhetsky geothermal system

The Pauzhetsky hydrothermal system is located in the southern part of Eastern volcanic belt of Kamchatka peninsula. Eastern volcanic arc is an extension of Kuril volcanic arc. Volcanic activity in this region is caused by subduction of Pacific oceans plate under the Eurasian continental tectonic plate. On the peninsula there are about 30 active volcanoes and several large eruptions occur every year.

Due to high volcanic activity, hydrothermal activity also takes place in this region. So it is reasonable to use geothermal energy to produce electricity. The first geothermal power station on Kamchatka peninsula is located on Pauzhetsky geothermal deposit (Figure. 2). Pauzhetskaya power station was commissioned in 1966 and works until now. It uses overheated steam from production wells with average depth of 300 meters. Water-bearing rocks are tuffs, that are covered by andesite lava flows.

The Pauzhetsky geothermal area is mainly composed of a sedimentary-volcanogenic complex of rocks (Figure 1). Most of them are covered with effusive and pyroclastic formations of basaltic, andesitic or dacitic composition. Sedimentary formations are mainly products of destruction of lava and tuff material, and occupy lower parts of the relief.

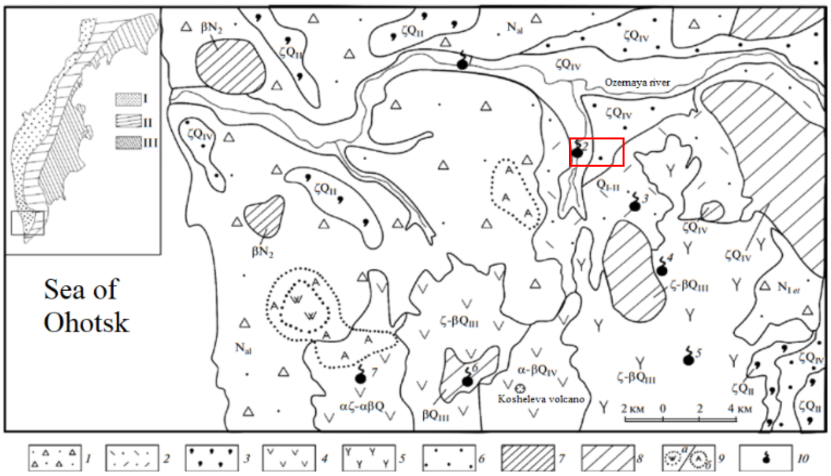

Figure 1: Location of the Pauzhetsky geothermal area and a schematic geological map of the area (according to Rychagoet al., 2012)

The inset shows the main volcanic belts of Kamchatka: I - West Kamchatsky, II - Central Kamchatsky, III - East Kamchatka. On the main scheme indicated: 1 - Lava pyroclastic deposits of Neogene age; 2 - volcanogenic rocks (tuffs and tuffites) of the Pauzhetskaya suite; 3 - ignimbrites; 4 - dacitic andesites - basaltic andesites of the Koshelevsky volcanic massif; 5 - volcanic rocks (lavas, pyroclastic flows, extrusions) of the Kambalny Ridge; 6 - pyroclastic deposits (pumice); 7, 8 - subvolcanic and extrusive bodies of Neogene (7) and Quaternary (8) age; 9 - fields of hydrothermally altered rocks, a - secondary quartzites, b - argillisites; 10 - main modern thermal anomalies of the area: 1 - First Hot Springs (Pioneer Camp), 2 - Second Hot Springs (Pauzhetsky deposit), 3 - North Kambalny, 4 - Central Kambalny, 5 - South Kambalny, 6 - Verkhne Koshelevsky, 7 - Nizhne Koshelevsky. □ - boundaries of Pauzhetskoe geothermal deposit

The hydrogeological structure of the Pauzhetsky geothermal deposit consists of the following units. The upper confining layer ('cap' rock) consists of low-permeable ash tuffs and tuffites, with interlayers of coarse-grained pumice tuffs. The main aquifer is found in highly permeable but totally zeolitized medium-coarse grained tuffs (N_2-Q_1 pau). The coefficient of permeability according to pumping data varies from 0.0025 to 0.035 Darcy, which is associated with a rather strong variability of rock properties along the section. The aquifer is underlaid by very low-permeability tuff breccias and welded vitric tuffs of the Golygin Horizon (N_2). The volcanic sandstones of Paleogene-Miocene age form the second (deep) aquifer complex (Naboko, 1965)

Figure 2: View of Eastern-Pauzhetsky thermal field.

A large explored part of the Pauzhetsky geothermal deposit is located on the northeastern slope of the Kambalny ridge, its other part, including the Pauzhetka geothermal power station, which is located on the right side of Pauzhetka river.

2.2. Characterization of the East Pauzhetsky thermal field

The Eastern Pauzhetsky thermal field is located on the northwestern slope of the Kambalny Range in the eastern part of the Pauzhetsky deposit at an altitude of about 300 m. In plan, it has a shape elongated in a sublatitudinal direction and linear dimensions of approximately 350x100 m (Figure 3).

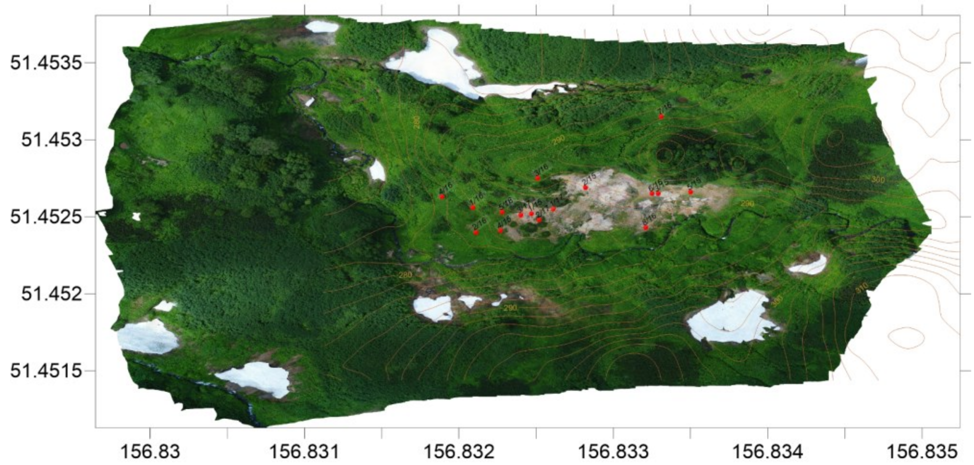

Figure 3: Location of wells in the East-Pauzhetsky thermal field area, placed on the terrain orthophotomap.

Various hydrothermal manifestations such as vapor-gas jets and boiling mud-water springs are developed on the East Pauzhetsky thermal field. In some places, the temperature of the rocks reaches 100 degrees Celsius at a depth of 50 cm. This thermal field is located far enough from the production wells, so the conditions for the existence and development of this thermal field can be called natural, and therefore the study of it is relevant.

The field was formed on andesites, which began to actively change under the action of thermal water and steam. The clay horizon was formed on the surface of the thermal field. The base of the hydrothermal clay stratum is represented by fractured and brecciated, intensely argillitized andesites (Figure 4). Fragments of primary andesites are rounded, or with smoothed edges, and consist of smaller fragments displaced relative to each other due to the formation of hydrothermal-metasomatic cement. The cement is an association of secondary minerals: smectites + chlorites + quartz + opal + carbonates + zeolites + sulfides. Separate rock sections are represented by relatively less modified, but fractured andesites.

3. MATERIALS AND METHODS

3.1. Samples

To study the full range of hydrothemal alteration, several samples were taken, including slightly changed andesites, medium altered andesites, andesitic metasomatic breccia, and hydrothermal clays. The specimens of altered andesites and breccia were taken from the wells, drilled on the field in 2015-2018. Eight samples of andesites from wells VPP-5/15 and VPP-8/16 were selected for laboratory study. Core samples from well VPP-5/15 are andesitic metasomatic breccia described above, and core samples from well VRP-6/16 are represented by less modified andesite broken by a large number of cracks filled with secondary minerals (Figure 5).

Figure 4: Andesitic metasomatic breccia (sample VPP-5/15-15)

Figure 5: Slightly altered fractured andesite (sample VPP-8/16-17)

Samples of slightly altered andesite were collected from the core of borehole 102 drilled at the Pauzhetsky field in the 20th century. Samples of hydrothermal clay-rich soils were taken from the well VPP- 2/16. Sampling was carried out at intervals of 20 cm. In total, 12 samples of clays soils were collected and tested.

3.2. Laboratory testing

Mineral diagnostics was carried out by transmitted light microscopy (Olympus BX-41). Then, quantitative evaluation of secondary minerals was made with X-ray diffraction (XRD) (Rigaku ULTIMA-IV). Microprobe analysis was conducted using electron microscope LEO 1450VP with microprobe apparatus INCA 300).

Applied laboratory methods to determine physical and mechanical properties were different for rocks and soils. The measurements for rocks were performed in accordance with standard of the International Society for Rock Mechanics (ISRM, 2007). In the laboratory each sample was separated into several specimens (from 1 to 4) for physical and mechanical measurements. Specimens had cylindrical shape with a length-to-diameter ratio 1:1. Several tests were carried out for each property, and finally the mean values were calculated for each sample. The studied properties include: density of air-dry (ρ) and water-saturated (ρ_w) rock, density of solid particles (ρ_s), hygroscopic moisture (W_g), porosity (n), water absorption (W), open porosity (n_o), magnetic susceptibility (χ), velocity of longitudinal waves along the axis of the cylinders in the air-dry (V_p) and water-saturated (V_{pw}) condition of the rock, velocity of the transverse waves along the axis of the cylinder in the air-dry (V_s) and water-saturated (V_{sw}) condition of the rock, Poisson's ratio along the axis of the cylinder (μ dyn), dynamic modulus of elasticity along the cylinder axis (E dyn), uniaxial compressive strength in air-dry (R_c) and water-saturated (R_{cw}) condition, softening coefficient (K_{soft}), uniaxial tensile strength in air-dry (R_p) and water-saturated (R_{pw}) condition.

Laboratory tests for hydrothermal clays were performed to determine: water content in situ (W_n), hygroscopic moisture (W_g), plastic (W_p) and liquid (W_L) limits, plasticity index (I_p), liquidity index (I_L), bulk (ρ), dry bulk (ρ_d), and solid particles (ρ_s) densities, porosity (n), porosity coefficient (e) and degree of humidity (G). Measurements were in accordance with ISO/TS 17892-10:2004.

4. RESULTS AND DISCUSSION

4.1. Changes in the composition of rocks in the section of the East Pauzhetsky thermal field

Original rocks forming the northwestern slope of the Kambalny volcanic ridge are represented by andesites. In the zone of rise and discharge of aggressive thermal waters in the East Pauzhetsky thermal field, andesites change greatly. As a result, the mineral composition varies considerably. Table 1 presents the results of studies of the mineral composition of both groups of samples, as well as a separate study of the mineral composition of debris and cement of breccia and the mineral composition of the material, filling the cracks of moderately altered andesites.

Table 1: Mineral composition of andesites by X-ray diffraction

Sample №	Composition of the sample	Sampling depth, cm	Mineral content, %											
			Plagioclase (albite-anortite)	Pyroxenes (augite, ferrosilite)	Potassium feldspar (microcline-orthoclase)	Quartz	Calcite	Zeolites (clinoptilolite, heilandite, mordenite)	Zeolites (stilbit)	Gypsum	Pyrite	Hematite	Smectite	Kaolinite
VPP - 5/15-15	Andesitic metasomatic breccia	280-300	8,2	8,2	11,8	20,8	1,4	1,7	1,3	0,6	-	1,3	39,8	4,5
VPP - 5/15-15-D	Debris from metasomatic breccia	280-300	6,8	3,4	14,8	32,2	1	2,2	2,4	1	0,5	1,1	31,2	3,5
VPP - 5/15-18-D		340-360	43,8	6,7	13,1	14,1	0,7	1,6	-	0,9	-	1,2	14,9	3
VPP - 5/15-15-C	Cement of metasomatic breccia	280-300	1,7	8,9	14	10,5	4,8	3,8	14,7	0,5	1,3	0,5	36,4	3
VPP - 5/15-18-C		340-360	4,5	5,1	10,9	11,1	6,6	9,4	18,4	1,1	2,6	0,3	26,5	3,1
VPP - 8/16-22	Moderately altered andesite	400-415	28,9	4,9	12,8	11,4	1,3	2,9	1,2	0,5	-	1,4	28,7	4,9
VPP - 8/16-29		495-505	9,2	9,2	13,8	22,8	1,4	2,7	2,3	0,6	-	2,6	29,8	4,5
VPP-8/16-24-T	Secondary minerals from cracks in moderately altered andesite	435-450	0,7	0,5	0,9	1,2	42,1	1,6	31,3	0,5	7,9	-	12,3	0,8

Table 2: Mineral composition of hydrothermal clays by X-ray diffraction

Sample №	Composition of the sample	Sampling depth, cm	Mineral content, %												
			Plagioclase (albite-anortite)	Pyroxenes (augite, ferrosilite)	Potassium feldspar (microcline-orthoclase)	Quartz	Calcite	Gypsum	Pyrite	Hematite	Smectite	Kaolinite	Anatase	Lomontite	Cristobalite
VPP-2/16-1	Hydrothermal clays	0.2-0.4	1,2		5,6	14,9	-	-	0,3		63,7	9,1	1,7	-	3,6
VPP-2/16-2		0.4-0.6	1,5		6,2	23,6	-	-	0,4		53,8	8,6	1,4	-	1,9
VPP-2/16-4		0.8-1.0	0,3		5,0	17,9	-	-	0,5		60,4	11,2	1,9	-	2,9
VPP-2/16-7		1.4-1.6	-		6,4	11,2	-	-	0,3		35,4	30,7	3,8	-	9,9
VPP-2/16-10		2.0-2.2	-		6,4	6,6	-	-	6,3		-	58,2	8,3	-	14,2
VPP-2/16-13		2.6-2.8	-		4,2	0,4	-	-	3,9		-	58,9	7,2	-	13,1
VPP-2/16-16		3.2-3.4	1,5		5,5	11,6	-	-	1,1		62,1	14,2	1,9	-	2,1
VPP-2/16-19		3.8-4.0	1,8		7,0	0,9		-	5,5		74,2	7,4	0,7	-	0,7
VPP-2/16-23		4.6-4.8	0,8		5,3	6,6	-	4,5	2,3		70,8	7,1	1,6	-	0,6
VPP-2/16-25		5.0-5.2	2,9		5,7	1,7	1,2	2,2	4,2		30,5	4,4	2,0	-	-
VPP-2/16-29		5.8-6.0	-		-	0,3	-	-	2,7		22,6	1,5	0,5	54,2	17,2
VPP-2/16-34		6.8-7.0	1,6		5,3	0,3	1,1	1,6	1,1		60,2	2,7	0,8	25,3	-

From Table 1 it is observed that with a decrease in the depth, the degree of alteration of the original andesites increases and the number of secondary minerals increases. Basically, there is an increase in the content of smectite (from 29% to 40%). There is a large difference in the composition of debris and cement of metasomatic breccia. The cement contains a large amount of zeolites (approximately 25%), whereas the debris contain only 10% in average. At the same time, the content of clay minerals (smectite and kaolinite) in debris is not much lower than the content of the same minerals in cement, which means that clay minerals already occupy a large part of andesite debris. Most likely, that clay minerals were the result of alteration of the main part of volcanic glass and began the transformation in crystals of the weakest minerals.

The upper horizon of the thermal field section is composed of hydrothermal clays.

In the lowermost part of the clay cover (4.8-7.0 m) gray lightweight clay is found, characterized by a very stiff consistency. Their mineral composition is dominated by smectite, mixed-layer minerals and laumontite; kaolinite, albite, quartz, cristobalite, pyrite and gypsum are present in smaller quantities (Table 2). The content of sand and dust fractions in samples of this clay is approximately equal (from 31 to 45%), the clay fraction is present in smaller quantities (24-25%). The sample VPP-2/16-29 differs in a lower content of the clay fraction (12%), the dust fraction is up to 53% (Figure 6).

Above the section (2.8-4.8 m), the horizon is also distinguished from heavy gray clay with a stiff and firm consistency. The mineral composition is represented mainly by smectite and in much smaller quantities by kaolinite, quartz, microcline, pyrite and gypsum are also present (Table 2). The total content of the clay fraction in this horizon increases upward to the section from 28 to 46%, the content of the dust fraction is 37-44%, and the sand content is 17–33% (Figure 6).

Further, in the range of 1.6-2.8 m, the horizon is light gray heavy clays with a soft (firm-soft) consistency. The mineral composition differs significantly from the rest of the horizons, kaolinite (up to 59%) and cristobalite strongly dominate in it; there is microcline, anatase and mixed-layer minerals in smaller quantities. In addition, this horizon is characterized by a high content of coarse-crystalline, relatively uniformly dispersed pyrite (Table 2). The granulometric composition shows the maximum content of the clay fraction in the section (58-77%) and the minimum of sand (6-7%); dust fraction varies in the range of 17-35% (Figure 6). At the macro level, clay is characterized by a pseudomorphic texture inherited from the primary rocks.

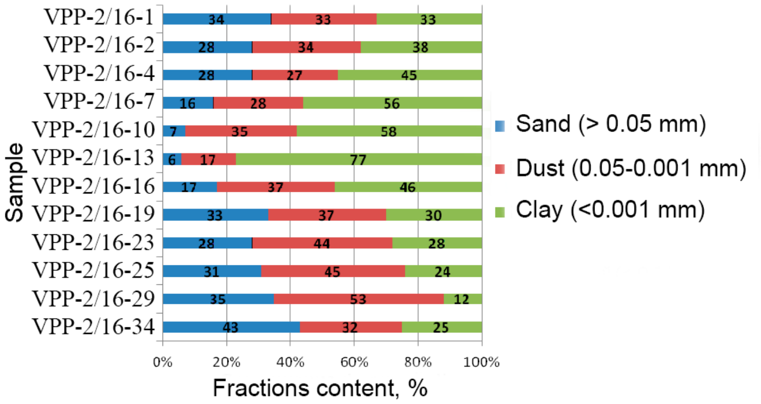

Figure 6. Particles size distribution in hydrothermal clay-rich soils

Clays of the upper horizon (0.2–1.6 m) are brown, from firm to very stiff consistency. Smectite, kaolinite, and quartz prevail in clay soils, while cristobalite, microcline, albite and anatase are found in smaller amounts. Brown color is provided by the presence of iron hydroxides. There is practically no pyrite (<1%). Up the section, the content of the clay fraction decreases from 56 to 33%, the content of sandy (from 16 to 34%) and dust (from 28 to 33%) fractions increases (Figure 6). This horizon belongs to the zone of sulfuric acid leaching.

4.2 Changes in the physical and mechanical properties of rocks in the section of the East Pauzhetsky thermal field

Table 3: Physical and mechanical properties of andesites

Degree of alteration	Sample №	Specimen №	ρ	ρ s	n	W	n₀	Vp	Vs	μ dyn	E dyn *10³	Rc	Rt	χ
			g/cm³	g/cm³	%	%	%	km/s	km/s	m/m	GPa	MPa	MPa	SI* 10³
Highly altered metasomatic breccia	VPP-5/15-15	1	2,32	2,98	22,0	-	-	-	-	-	-	-	-	20,60
		2	2,24	2,98	24,8	-	-	-	-	-	-	10,7	-	18,51
		3	2,29	2,98	23,0	5,1	11,8	2,56	1,66	0,13	14,42	-	-	21,69
		4	2,14	2,98	28,1	-	-	-	-	-	-	-	0,7	17,85
		5	2,10	2,98	29,5	5,7	12,0	2,68	1,70	0,16	14,16	-	-	18,93
	VPP - 5/15-16	1	2,46	2,89	14,9	-	-	-	-	-	-	-	-	20,80
		2	2,40	2,89	16,8	-	-	3,17	1,70	0,30	18,06	14,5	-	18,87
		3	2,45	2,89	15,3	3,6	8,9	3,24	1,73	0,30	19,08	-	-	20,79
		4	2,38	2,89	17,6	-	-	3,05	1,68	0,28	17,21	-	6,0	16,29
		5	2,45	2,89	15,2	2,9	7,1	2,92	1,67	0,26	17,22	-	-	21,63
	VPP - 5/15-17	1	2,32	2,89	19,5	-	-	-	-	-	-	-	-	21,40
		2	2,28	2,89	21,2	-	-	-	-	-	-	14,7	-	20,52
		3	2,27	2,89	21,4	-	-	3,08	1,61	0,31	15,49	-	-	18,66
		4	2,20	2,89	23,9	-	-	2,37	1,48	0,18	11,33	-	2,5	15,03
	VPP - 5/15-18	1	2,08	2,77	25,0	-	-	-	-	-	-	2,31	-	2,34
	average		2,29	2,91	21,2	4,3	9,9	2,88	1,65	0,24	15,87	10,6	3,1	18,26
Medium altered andesites	VPP - 8/16-22	1	2,71	2,82	3,8	0,4	1,0	4,11	2,30	0,27	36,56	-	-	45,6
	VPP - 8/16-24	1	2,32	2,90	20,1	-	-	2,70	1,44	0,30	12,47	19,7	-	34,2
	VPP - 8/16-29	1	2,31	2,99	22,8	-	-	3,38	1,66	0,34	17,00	-	3,3	28,35
		2	2,37	2,99	20,6	-	-	2,71	1,41	0,31	12,44	20,8	-	31,5
	VPP - 8/16-30	1	2,59	2,89	10,5	-	-	3,79	1,98	0,31	26,58	69,8	-	41,4
		2	2,53	2,89	12,5	0,6	1,4	4,15	2,13	0,32	30,36	-	-	36,6
		3	2,57	2,89	11,2	-	-	-	-	-	-	-	6,3	41,4
	average		2,48	2,91	14,5	0,5	1,2	3,47	1,82	0,31	22,57	36,8	4,8	37,01
Slightly altered andesites	102-5	1	2,69	2,80	3,0	-	-	5,53	2,71	0,34	52,91	155	16,2	32,0
		2	2,68	2,80	2,7	-	-	4,88	2,42	0,34	42,06	87	-	42,3
	102-1		2,70	2,80	2,9	-	-	4,12	2,01	0,34	29,27	115	9,1	41,7
	average		2,7	2,8	2,9	-	-	4,85	2,38	0,34	40,83	119	12,7	38,67

For most of the studied parameters, the relationship between the degree of hydrothermal alteration and the value of the property index is clearly visible in Table 3.

The density of rocks decreases with increasing of alteration degree (Figure 7). This is due to the fact, that the density of andesites (2.5-2.6 g/cm^3) is higher than the density of zeolites and clay minerals (1.8-2.3 g/cm^3), which replace the primary components of andesites. In addition, the formation of secondary minerals is accompanied by a strong increase in porosity.

The density of solid particles increases as alteration increases. For slightly altered samples, the density of solid particles is 2.80 g/cm^3, and for moderately and highly altered rocks ρs = 2.91 g/cm^3. This is most likely due to the fact that pyrite and hematite, having a higher density, are formed in the rock under the influence of aggressive thermal waters.

The porosity of andesites also has a clear dependence on the degree of alteration (Figure 8). For slightly altered andesites, the average value of porosity is 2.9%, for the second group is 14.5%, and for the third group is 21.2%. This change in porosity is associated with a gradual increase in the amount of secondary minerals, such as zeolites and clay minerals, which have a much greater porosity than the original andesites. The tendency of change in porosity shows that the leaching process dominates during hydrothermal alteration of rocks.

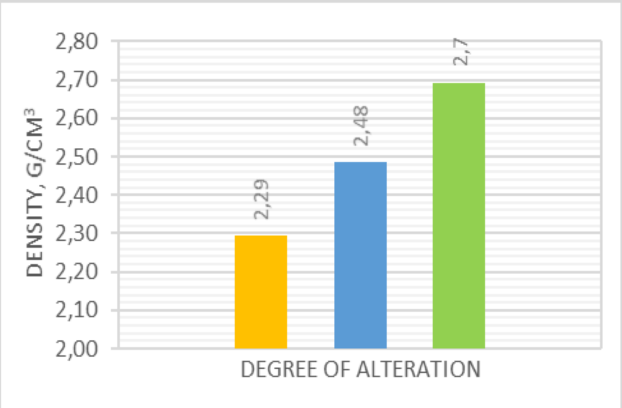

Figure 7: Relationship between the density of andesites and degree of hydrothermal alteration.

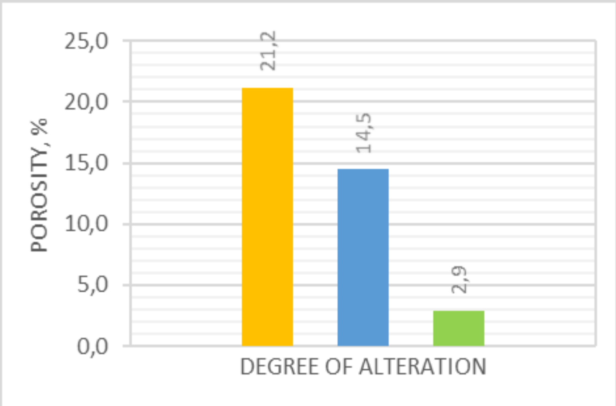

Figure 8: Relationship between porosity of andesites and degree of hydrothermal alteration.

Highly altered metasomatic breccia Moderately altered andesites Slightly altered andesites

Water absorption and open porosity also increase with an increase in the degree of alteration. For moderately altered andesites, water absorption is 0.5% and open porosity is 1.2%, while for highly altered rocks water absorption is 4.4% and open porosity is 9.9%. This is due to the formation of secondary minerals (clays and minerals of the zeolite group) with high porosity.

The velocities of ultrasonic waves evenly decrease with increasing of alteration degree, from V_p = 4.85 km/s in slightly altered andesites to V_p = 2.88 km/s in strongly altered andesite breccias (Figure 9). This is explained by the fact that the main factors affecting the velocity of ultrasonic waves in rocks are density, porosity, and mineral composition. Changing all of these factors affects the values of V_p and Vs. At the same time, the greatest contribution to the decrease in the ultrasonic velocities is the change in the structure of the rock under the influence of secondary alterations. The ultrasonic velocities in a water-saturated state were measured only for two samples of moderately altered andesites (they did not change, relatively dry state), since the other specimens were destroyed after saturation.

The dynamic modulus of elasticity decreases with increasing of alteration degree. The values of elastic modulus decrease from 40.83 GPa in slightly altered andesites, down to 21.60 GPa in moderately altered rocks and finally to 15.87 GPa in highly altered metasomatic andesite breccia. Elastic modulus directly correlates with density and detects an inverse relationship with porosity.

Magnetic susceptibility decreases with increasing alteration degree (Figure 10). The average value of magnetic susceptibility for slightly altered andesites is 38.67 x 10^{-3} SI, moderately altered andesites is 37.01 x 10^{-3} SI, and highly altered andesite breccia is 18.26 x 10^{-3} SI. High values of magnetic susceptibility in the original andesites are associated with the presence of ferromagnetic (titanomagnetite) and paramagnetic (augite, hornblende) minerals. The decrease in magnetic susceptibility by half with an increase in the alteration degree is apparently associated with the replacement of primary magnetic minerals with less magnetic secondary minerals (quartz, clay minerals, zeolites, etc.). Although pyrite appears among secondary minerals, it is significantly less magnetic than primary titanomagnetite.

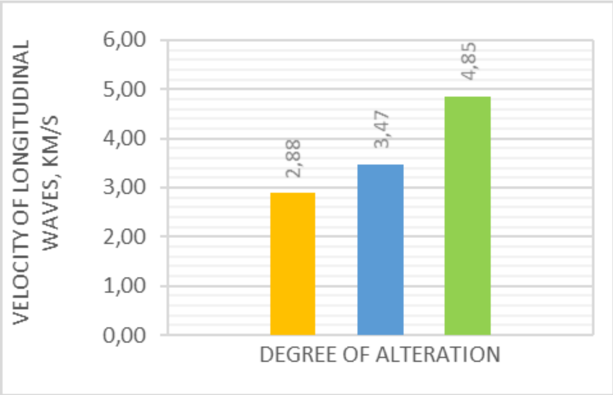

Figure 9: Relationship between velocity of longitudinal waves of andesites and degree of hydrothermal alteration.

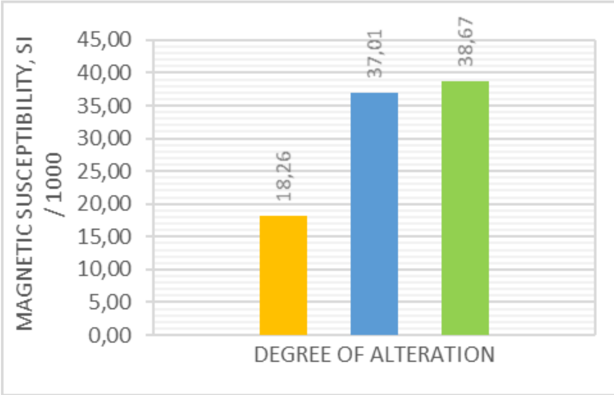

Figure 10: Relationship between magnetic susceptibility of andesites and degree of hydrothermal alteration.

Highly altered metasomatic breccia Moderately altered andesites Slightly altered andesites

The variation of uniaxial compression strength in an air-dry state is characterized by a common trend. It decreases with an increase in the alteration degree (Figure 11) from 119 MPa in slightly altered andesites down to 36.8 MPa in moderately altered andesites, and then to 10.6 MPa in highly altered metasomatic andesite breccia. Apparently, the trend of strength reduction is explained by the developing of soft secondary minerals, leaching of rocks with formation of secondary porosity, and formation of cracks. During compression tests, the specimens of highly altered andesite breccia were destroyed by contacts between the debris and cement. It means that strength of rock is controlled by the strength of secondary minerals cementing the debris. The failure of moderately altered andesites was along inclined cracks with angle of 45 degrees to the horizon.

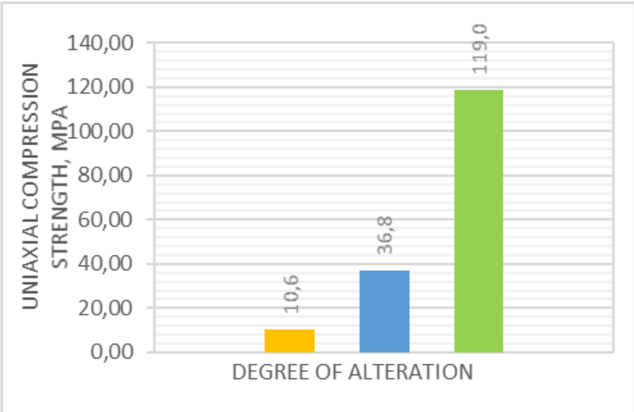

Figure 11: Relationship between uniaxial compression strength of andesites and degree of hydrothermal alteration.

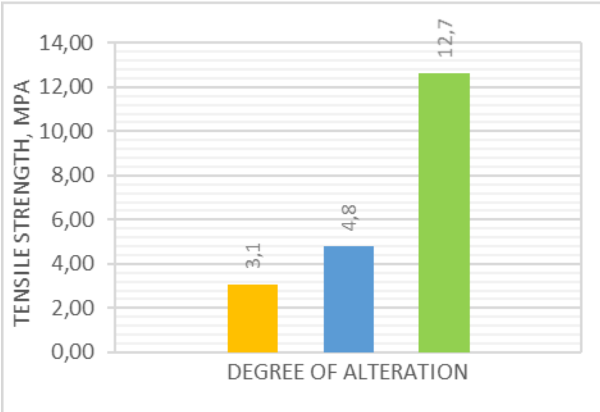

Figure 12: Relationship between tensile strength of andesites and degree of hydrothermal alteration.

Highly altered metasomatic breccia Moderately altered andesites Slightly altered andesites

The tensile strength in the air-dry state changes in a manner analogous to the change in the uniaxial compression strength, depending on the alteration degree (Figure 12). Slightly altered andesites have the maximum tensile strength due to the absence of intense fracturing as in more altered andesites. The value of tensile strength is reduced three times, from 12.7 MPa in slightly altered andesites, down to 4.8 MPa in moderately altered ones, and finally to 3.3 MPa in strongly altered rocks. Samples of highly altered andesites were destroyed by debris contacts, and moderately altered ones by two half-cylinders.

The interaction with water has a negative effect on the strength properties. Most of the samples, after keeping in water during a week were destroyed. This was especially noticeable for metasomatic breccia, which contain 30-40% of clay minerals.

Table 3: Properties of clay-rich soils

Sample	Sampling depth, m	Temperature, °C	Moisture, %					Plasticity index, I_P	Liquidity index, I_L	Density, g/cm³			Porosity, n	Porosity coefficient, e	Degree of humidity, G
			Situ W	Hygroscopic, W_2	Plastic limit, W_p	Liquid limit, W_L	Maximum molecular capacity, W_{mmc}			Bulk, ρ	Dry bulk, ρ_d	Solid particles, ρ_s			
VPP-2/16-1	0.40	23	44	4.5	45	70	31	25	-0.04	1.57	1.09	2.63	0.59	1.41	0.81
VPP-2/16-2	0.60	27	47	3.4	39	68	26	29	0.28	1.67	1.14	2.68	0.57	1.35	0.94
VPP-2/16-4	1.00	32	49	3.8	41	82	29	41	0.20	1.71	1.15	2.65	0.57	1.30	0.99
VPP-2/16-7	1.60	38	65	3.6	49	87	29	38	0.42	1.60	0.97	2.71	0.64	1.79	0.99
VPP-2/16-10	2.20	48	81	1.9	37	91	28	54	0.81	1.55	0.86	2.87	0.70	2.34	1.00
VPP-2/16-13	2.80	56	97	2.0	39	100	37	61	0.95	1.47	0.75	2.74	0.73	2.65	1.00
VPP-2/16-16	3.40	65	55	4.6	38	82	31	44	0.39	1.67	1.08	2.71	0.60	1.51	0.99
VPP-2/16-19	4.00	81	43	5.3	36	82	29	46	0.15	1.79	1.25	2.77	0.55	1.22	0.98
VPP-2/16-23	4.80	95	45	5.6	39	73	31	34	0.18	1.77	1.22	2.73	0.55	1.24	1.00
VPP-2/16-25	5.20	97	26	4.4	31	57	24	26	-0.19	1.79	1.42	2.79	0.49	0.96	0.75
VPP-2/16-29	6.00	99	27	3.8	28	53	22	25	-0.04	1.75	1.38	2.68	0.49	0.94	0.76
VPP-2/16-34	7.00	105	21	5.5	27	53	23	26	-0.23	1.77	1.46	2.59	0.44	0.77	0.70

The density of solid particles (ρ_s) varies from 2.59 to 2.87 g/cm^3. The high values of ρ_s are observed in the middle part of the section. The highest value 2.87 g/cm^3 (sample VPP-2 / 16-10) correlates with high content of pyrite and anatase (Table 3). The dry bulk density of the soil (ρ_d) varies in the range from 0.75 to 1.46 g/cm^3. It is maximum in the lower part of the clay horizon and gradually decreases upward the section, but in the near-surface layer (0.2-1.6 m) it rises again up to 1.09-1.15 g/cm^3.

The plastic limit (W_P) is generally in the range of 37–49% and only in the lower part of the section it decreases to 31–27%. The liquid limit (W_L) constantly increases from the surface to a depth of 2.8 m from 70 to 100%, then continuously decreases to 53% at the base of the clay horizon. The plasticity index (I_P) also increases from the surface down to a depth of 2.8 m (from 25 to 61%) and returns again to 25% at the base of the section. The consistency varies upwards along the section from very stiff (I_L <0) at the base of the clay horizon to soft-firm ($0.75 < I_L \leq 1.00$) in a depth of 2.0-2.8 m, but in the near-surface layer, the soil is again classified as stiff and very stiff.

5. CONCLUSION

The East Pauzhetsky thermal was formed on andesites, which are intensively altered under the action of thermal water and steam. During hydrothermal alteration, primary components (volcanic glass, phenocrysts of plagioclases, pyroxenes, amphiboles, and feldspar) transform to the secondary minerals typical for argillic zone (smectite, high-silica zeolites, quartz, calcite, and pyrite).

Three horizons are distinguished down to a depth of 7–8 m: hydrothermal clays, forming the cover on the surface of the field, andesite breccia, and altered fractured andesites. The maximum alteration of rocks is achieved in the near-surface horizon where initial andesites are totally altered and transformed to hydrothermal clays.

Hydrothermal alteration of rocks influences on their physical and mechanical properties. Physical and mechanical properties decrease with an increase of porosity (from 2.9% to 21.2%) and degree of hydrothermal alteration. Density varies from 2.7 g/cm^3 to 2.29 g/cm^3, velocity of longitudinal waves changes from 4.85 km/s to 2.88 km/s, dynamic modulus of elasticity reduces from 40.83 GPa to 15.87 GPa, uniaxial compression strength decreases from 119 MPa to 10.6 MPa. Magnetic susceptibility is also reduced two times (from 38.67 x 10^{-3} to 18.26 x 10^{-3} SI) due to decomposition of titanomagnetite, as well as paramagnetic minerals such as augite and hornblende.

It should be emphasized that argillic alteration of andesites and a corresponding decrease in their mechanical properties promote a wide range of geological phenomena such as slopes instability and landslides, surface deformation, migration of thermal manifestations, change of relief.

REFERENCES

Frolova, J., Ladygin, V., Rychagov, S.: Petrophysical properties of argillitization zone in geothermal fields. *Geothermal Resource Council Transactions*, (30), (2006), 909-912.

International Society on Rock Mechanics. In: Ulsay, R., Hudson, J. (Eds.), The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. ISRM. 628 p (2007)

ISO/TS 17892-10:2004 Geotechnical investigation and testing -- Laboratory testing of soil (2004)

Mielke, Ph., Prieto, A., Bignall, G., Sass I.: Effect of Hydrothermal Alteration on Rock Properties in the Tauhara Geothermal Field, New Zealand. *Proceedings* World Geothermal Congress 2015 Melbourne, Australia, 19-25 April 2015. https://www.geothermal-energy.org/pdf/IGAstandard/WGC/2015/12081.pdf

Naboko S.I. Hydrothermal Metamorphism of Rocks and Mineral Formation / S.I. Naboko, G.A. Karpov, A.P. Roznikova. In book: *Pauzhetskiya hot waters in Kamchatka*. M.: Nauka, 1965. – p. 76-118.

Navolet, V., Geraud, Y., Diraison, M., Mercier De Lepinay, J. and Munschy, M.: Physical properties of fresh or hydrothermalized volcanic rocks from the west coast of Basse-Terre and Terre-de-Haut (Guadeloupe archipelago). *Proceedings,* European Geothermal Congress 2016, Strasbourg, France.

Pola, A., Crosta, G., Fusi, N. and Barberini, V.: Influence of alteration on physical properties of volcanic rocks, *Tectonophysics* 566-567 (2012) 67–86.

Potro, R., Hürlimann, M.: The decrease in the shear strength of volcanic materials with argillic hydrothermal alteration, insights from the summit region of Teide stratovolcano, Tenerife. J. Eng. Geol. (2009) 104 (1–2), 135–143. https://doi.org/10.1016/j.enggeo.2008.09.005

Rychagov, S.N., Sokolov, V.N., Chernov, M.S.: Hydrothermal clays of South Kamchatka's geothermal fields: a new approach and study results. *Geochemistr*y (2012) 4. pp. 378-392.

Siratovich, P., Davidson, J., Villeneuve, M., Gravley, D., Kennedy, B, Cole, J., Wyering, L., and Price, L.: Physical and mechanical properties of the Rotokawa andesite from production wells RK 27_l2, RK 28 and RK 30, *Proceedings,* New Zealand Geothermal Workshop (2012) Auckland, New Zealand.

Wyering, L., Villeneuve, M. and Wallis, I.: The effects of hydrothermal alteration on mechanical rock properties of the andesite breccia and Tahorakuri formation from the Ngatamariki geothermal field, New Zealand and empirical relations between rock strength and physical properties, *Proceedings,* New Zealand Geothermal Workshop (2012) Auckland, New Zealand.