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Alteration of volcanic rocks and changes in physical-mechanical properties on the South-Kambalny thermal field (South Kamchatka)

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Abstract. The aim of this research project was to consider hydrothermal alteration of volcanic rocks and accompanying changes in their physical and mechanical properties on the thermal field of South Kamchatka. Under the influence of thermal water and steam original andesites and basaltic andesites gradually transform to clay-rich soils and then to opalites and secondary quartzites. The changes in the mineral composition, microstructure, and physical-mechanical properties of rocks and soils in the thermal field were studied. Argillic hydrothermal alteration has gradually decomposed andesites to weak clay-rich soils which form a cover above the field. Elevated sites on the thermal field are composed of opalites and monoquartzites. Progressive hydrothermal alteration of andesites and changes in their properties promotes a broad range of geological phenomena including initiation of landslides, migration of thermal manifestations, changes in relief, and surface deformation.

1 Introduction

Geothermal energy is one of non-conventional sources, which is used for electricity production in 23 countries and for heat supply in more than 80 countries. In Russia the richest geothermal heat reservoirs occur in the Kuril-Kamchatka volcanic arc, where tens of low- and high-temperature hydrothermal systems are located. Discharge of thermal water and steam on the surface leads to formation of thermal fields, which are characterized by high concentration of thermal manifestations. The host rocks interact with thermal fluids and undergo intensive transformations, usually consisting in their argillization. Hydrothermal argillization is a metasomatic replacement of the parent rocks by clay minerals. Generally argillic zones are formed at shallow depth due to rocks interaction with low-temperature thermal fluids (T=50-150°C). Depending on the parameters of fluids (temperature, composition and pH) various secondary minerals assemblages are formed such as zeolite-smectite, smectite, kaolinite-smectite, kaolinite, opal-kaolinite, alunite, and

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opalites. Many researches have observed that clay minerals, replacing the primary components of volcanic rocks, significantly weaken materials reducing their density and strength [1-5]. In turn, progressive hydrothermal alteration of rocks and changing the properties promotes a broad range of geological phenomena including slope instability and failure with the initialization of landslides, hydrothermal explosions, migration of thermal manifestations, and surface deformation and subsidence. These processes have an influence on the exploitation of geothermal field, and in some cases, they could prove to be hazardous for the economic or tourist development of geothermal site. The aim of the paper is to consider the entire range of hydrothermal alteration products and changes in properties of volcanic rocks along the section of South-Kambalny thermal field located in the south of the Kamchatka Peninsula.

2 Geological setting

South Kamchatka is characterized by intense hydrothermal activity concentrated within the Pauzhetsky volcanic-tectonic depression, representing one of the largest geothermal structures with a number of thermal fields present at the surface [6]. The Kambalny volcanic ridge is a tectonic-magmatic uplift within the Pauzhetsky depression. Three groups of thermal fields, including North-, Central-, and South-Kambalny, are located along the axial part of the ridge, elongated submeridionally at 18–20 km. The South-Kambalny group includes three thermal fields. One of these fields (Far South-Kambalny) is the subject of the present study. It is the largest field and the closest to the active volcano Kambalny. This part of the ridge is a complex stratovolcano ($Q_{2\text{-}3}$) consisting of ancient destroyed cones, as well as extrusive domes and subvolcanic bodies. The composition of rocks varies from basaltic andesite to dacite. The rocks composing the studied field are low-alkali moderately potassium andesites or basaltic andesites. The studied thermal field is located in the U-shaped valley of a creek, extended in SW-NE direction for 1.2 km. Thermal manifestations are represented by steaming soils, mud-water boiling springs, and gas-steam vents. The temperature of the water in boiling springs and in the mouths of the gas-steam vents reaches 103-104°C, and the soil near the surface is heated up to 107°C. The composition of thermal waters is dominated by weakly acidic and acidic sulphate solutions, the composition of gas is carbon dioxide and hydrogen sulfide. The surface of the thermal field is composed of hydrothermal clays and opalites, which are formed due to alteration of volcanic rocks under the action of sulphuric acid leaching (Fig.1).

3 Sampling and methods

3.1 Sampling

To study hydrothermal alteration of rocks, representative samples were collected across the thermal field, from fresh volcanic rocks to totally altered rocks. Clay-rich cover was investigated using open pit (2 m in depth), where 8 monoliths were selected.

3.2 Applied methods

Fluorescence (XRF) was performed to determine the chemical composition of the samples. 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 methods to determine physical-mechanical properties were different for rocks and soils. The measurements for rocks were performed in accordance with [7]. The studied properties include dry bulk (ρ) and specific (ρ_s) densities, effective (n_o) and total (n) porosity, hygroscopic moisture (W_g), water absorption (W), velocity of ultrasonic P- and S-waves (V_p, V_s), magnetic susceptibility (χ), elastic modulus (E), and uniaxial compressive strength (UCS). Laboratory tests for soils were performed to determine the water content in situ (W), 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 specific (ρ_s) densities, porosity (n), and shear strength parameters. The measurements were done in accordance with [8].

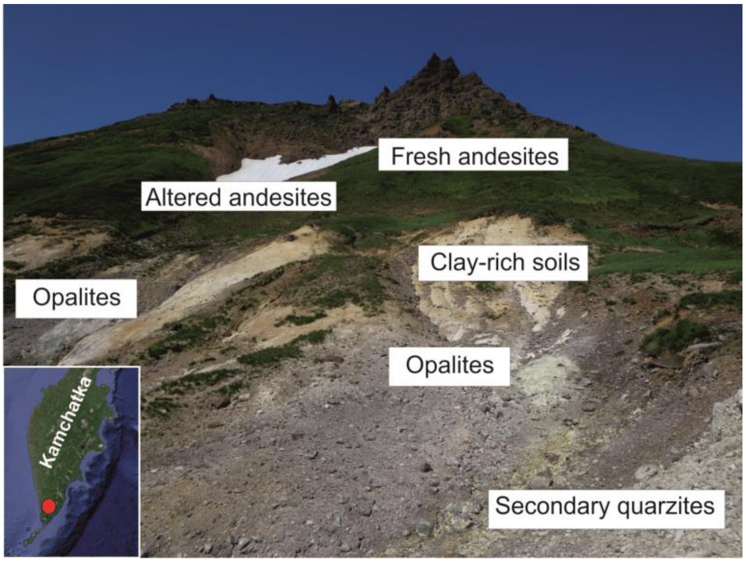

Fig. 1. Location of South-Kambalny thermal field and distribution of rocks in the thermal field.

4 Initial alteration of andesites

4.1 Fresh andesites

The thermal field is formed of basaltic andesite with dark gray colour, massive structure, and porphiritic texture. Plagioclase is prevalent among the phenocrysts, whereas pyroxene and potassium feldspar occur in smaller amount. The groundmass consists of volcanic glass and microcrystals. Among the microliths, both plagioclase and pyroxenes are present. Ore minerals are noted in the amount of 1-2%. Initial andesites are very dense (ρ=2.72 g/cm^3), low-porosity (n up to 7%), with high values of elastic parameters (V_p=5.15 km/s, E=53 GPa) and strength (UCS=128 MPa). They are characterized by high values of magnetic susceptibility ($\chi=34\cdot10^{-3}$SI), which is due to the presence of titanomagnetite and pyroxenes.

4.2 Slightly altered

Alteration starts from partial replacement of volcanic glass by smectites and opal, and a slight leaching of plagioclase phenocrysts. The SEM image shows how dense homogeneous volcanic glass, located in the interstitium between microliths, is transformed into an opal-smectite substance with a flaky microstructure. The thinnest films of opal are formed in microcracks, the size of opal grains is 50-100 nm. Mineral alteration results in a doubling in porosity and decrease in density. In turn, an increase in porosity causes a slight decrease in strength and elastic properties. Magnetic susceptibility decreases by a factor of two as a result of the partial decomposition of titanomagnetite and mafic minerals.

4.3 Moderately altered

Progressive alteration increases the amount of smectites up to 16-18% and opal. In addition, kaolinite, anatase, and gypsum appears in small amount. At this stage, the leaching process is distinctly manifested resulting in an increased porosity up to 20%, and on the contrary, decreases in the density, elasticity and strength properties. The decrease in magnetic susceptibility continues, its values are reduce by a factor of three. Thus, changes in the properties of the original rocks (an increase in porosity from 6–7% to 17–20%, and a decrease in strength by three times) contribute to more intensive further alteration of andesites, up to the transformation into hydrothermal clays and siliceous rocks.

5 Clay-rich soils

In the near-surface horizon, andesites are totally disintegrated and transformed into hydrothermal clay-rich soils, which forms a cover over thermal field, with a thickness of several meters. The horizon of hydrothermal clays is subdivided in two layers with different mineral composition. XDR analysis shows that the upper zone (down to the depth of 1 m) is characterized by a high content of dispersed opal (18-54%), kaolinite (14-34%), and smectite (10-17%). The clays of the lower zone are characterized by a high content of illite (46–49%), lower content of kaolinite (7–27%) and significantly decreased amount of opal (up to 11%). The content of quartz changes irregularly along the section, varying from less than 1% to 39%. Pyrite (up to 11%), cristobalite (up to 2%), alunite (up to 6%), and goethite (up to 4%) are present in clay-rich soils. Hydrothermal clays are characterized by high porosity (n=55-79%) and water content (W=40-131%), where higher values are characteristic for the upper layer, which is caused by a cellular microstructure of clays, while in the lower part of the section the structure is more dense. The consistency of clays varies from very soft in the upper part to stiff in the basement of the clay cover. It should be noted, that the very soft consistency of soils is related to high water content (W=131%), which is slightly higher than liquid limit (W_L=129%), whereas in situ the soil looks like the stiff type, so we call it "latent-soft". The reason is high content of microcrystalline and amorphous siliceous minerals, which built a rigid frame in clay-rich soils. Generally, hydrothermal clays are weak and soft soils with extremely low values of strength.

6 Siliceous rocks

The final products of hydrothermal alteration are sulphur opalites and monoquarzites, which are formed around the thermal waters discharges and steam-gas vents, confined to a network of cracks in the volcanic massif under the action of acid thermal steam. Generally, they compose elevated sites on the thermal field.

6.1 Secondary quartzites

The mineral composition of secondary quartzites is rather homogeneous: metasomatic quartz (95%) prevails, with a small amount of gypsum and anatase and relicts of initial plagioclase and feldspar (~ 3%). Microcrystalline quartz (50-200 μm) completely replaces the original rock. Only some outlines of primary minerals can be distinguished. It should be noted that idiomorphic microcrystals of quartz are formed in cavities and veins, under conditions of free growth, whereas the groundmass of andesites is replaced by firmly fused quartz grains with xenomorphic rough shape. Two differences are distinguished among monoquartzites: relatively dense (n=18%) and highly porous (n=45%). The former have high strength and elastic properties, because they consist of densely fused quartz microcrystals; the latter are low-strength rocks due to high porosity. Quartzites have very low and even negative values of magnetic susceptibility, and belong to the class of diamagnetics.

6.2 Sulphur opalites

Sulphur (up to 50%) and minerals of amorphous silica predominate in composition of sulphur opalites, kaolinite, gypsum, quartz, pyrite, and anatase are also present, but in smaller amount. Colloidal sulphur develops in the rock groundmass, and fine-crystalline sulphur develops in cavities and cracks. The largest accumulations of sulphur are confined to elevated microrelief sites, which are probably the old sulphur bumps. The displacement of gas-steam vents and thermal waters over the field is probably associated with geological processes, such as variation of the groundwater level, "deterioration" of physical and mechanical properties of rocks during hydrothermal alteration, initiating landslide processes within the field, changes in the porous structure and filtration properties of massif (sedimentation in cracks, on the one hand, and leaching and formation of secondary porosity, on the other). Generally, sulphur opalites are the weak rocks, which easily collapse and initiate landslide processes.

7 Conclusion

Successive stages of hydrothermal alteration are distinguished on the South-Kambalny thermal field: unchanged basaltic andesites → slightly altered andesites → medium altered andesites. Further alteration is subdivided into two branches, one of which leads to formation of clay-rich soils, whereas another produces opalites and monoquartzites. Hydrothermal clays form a cover of several meters thick above the thermal field. Siliceous rocks form elevated sites within thermal area. Gradual leaching of primary minerals and the formation of new voids under the action of thermal fluids is generally accompanied by a decrease in density, elastic and strength properties of initial basaltic andesites. The exceptions are monoquartzites, which consist of densely fused quartz microcrystals providing increased strength and elasticity. It should be noted that progressive hydrothermal alteration of andesites and changing in their properties promotes a broad range of geological phenomena including slopes instability with the initialization of landslides, migration of thermal manifestations, changing in relief, and surface deformation.

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