Alteration of volcanic rocks on the geothermal fields of Kuril-Kamchatka arc

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ABSTRACT: The paper focuses on the alteration of volcanic rocks in near-surface zone in geothermal fields of Kuril-Kamchatka arc (Far East, Russia). The mechanism of transformation of hard volcanic rocks with brittle failure into plastic clays with ductile deformation is described in details on macro- and micro-scale. Special attention is given to the variation of the physical and mechanical properties which occur due to geothermal alteration.

1 INTRODUCTION

Geothermal energy is presently used in many countries for electricity production and heat supply (Lund & Bertani 2010). Furthermore geothermal areas are very attractive touristic sites. In Russia the most promising is the Kuril-Kamchatka island arc which is located in the northwestern segment of Circum Pacific Belt. Tens of low- and high-temperature hydrothermal systems are placed in this region; several geothermal power plants are operated there. The hydrothermal systems are hosted in volcanic formations of Neogene-Quaternary age. Thermal waters with different temperature and chemical composition act on the rocks changing their mineralogy, pore-space morphology and finally changing their physical and mechanical properties. Under the action of thermal water they become intensely altered to e.g. propylites, zeolitic rocks, argillaceous rocks, hydrothermal clays, secondary quartzites, opalites, and quartz-feldspar metasomatises. Physical and mechanical properties of rocks change widely (Wyering et al. 2014, Frolova et al. 2014). Our previous studies have shown that these changes depend on a number of factors including parent rocks, pressure and temperature conditions, composition and type of fluid, and duration of fluid-rock interaction (Frolova et al. 2011, 2014).

In the near-surface horizon of geothermal fields, which can be the foundation for power plants construction (buildings, pipelines etc.), volcanic rocks transform into argillified rocks, hydrothermal clays or opalites. Hydrothermal clays are the most problematic horizon. They often form a very heterogeneous cover several meters thick which is characterized by high porosity, plasticity, hygroscopicity, and compressibility, increased weakness and occasionally swelling. Slope geological processes (landslides, mudflows) frequently develop in connection with hydrothermal clays due to their weakness and high compressibility especially in wet conditions.

Figure 1. Location of the studied hydrothermal fields: 1 – Baransky, 2, 3 – Koshelevsky and Pauzhetsky, 4 – Geysers Valley.

The main target of this research is to describe the transformation of volcanic rocks into clayey soil. Mineralogy of hydrothermal clays is relatively well-studied but engineering geology data are limited, so special attention is given to the variation of the physical and mechanical properties which accompanies geothermal alteration.

Transformation of volcanic rocks into hydrothermal clays were studied in detail in several thermal fields such as Koshelevsky, Pauzhetsky (South Kamchatka), Geysers Valley (Central Kamchatka) and Baransky (Iturup Island, the Kurils) (Fig. 1). In this research we consider the alteration at the Low-Koshelevsky thermal field as an example.

2 GEOLOGICAL AND GEOTHERMAL CONDITIONS

Koshelevsky hydrothermal system occupies the southernmost position on the Kamchatka Peninsula.
and is located on the slope of a volcano of the same name. It is a high-temperature, steam-dominated system presently under investigation (Rychagov et al. 2012). Temperatures reach 260°C at 1100 m depths (Belousov & Sugrobov 1976). The host rocks consist of effusive and volcanoclastic formations of Neogene-Quaternary age. Several thermal fields are known within the Koshelevsky volcano; two of those are very large i.e. – Low- and Upper-Koshelevsky – and differ in their geochemical and thermodynamic conditions. The cover of hydrothermal clays is characteristic for Low-Koshelevsky field (T = 70–100°C) and a surface zone of acid sulphate leaching with opalites is developed in the Upper-Koshelevsky field. Totally 24 samples of andesites were taken from natural outcrops and three trial pits (2 meter deep) on the Low-Koshelevsky field and 3 samples of hydrothermal clay were taken from trial pit (depth 35–55 cm, 80–100 cm, and 120–140 cm).

3 APPLIED METHODS

In the laboratory each sample was separated into several specimens (from 2 to 6) for physical and mechanical measurements. Specimens had cylindrical shape with a length-to-diameter ratio from 1:1 to 2:1. Several tests were carried out for each property, and finally the mean value was calculated for each sample. All laboratory tests were performed in accordance with the standards of the International Society for Rock Mechanics (ISRM 2007). Physical and mechanical properties include bulk density (\(\rho_b\)), grain density (\(\rho_g\)), open (effective) (\(n_o\)) and total (\(n_t\)) porosity, gas permeability, hygroscopic moisture (\(W_f\)), water absorption (\(W_a\)), velocity of ultrasonic P- and S-waves (\(V_p, V_s\)), elastic modulus (E), Poisson’s ratio (\(\nu\)), uniaxial compressive strength (UCS), tensile strength (\(\sigma_t\)), and shear strength parameters.

Total porosity was calculated through grain and bulk densities. Determination of water absorption and open (effective) porosity was made using water saturation techniques at room temperature and atmospheric pressure. Water absorption capacity by mass (in percent) was calculated as the mass of the absorbed water divided by the mass of dry rock. Subsequently, the open porosity was calculated through water absorption capacity, bulk density and density of water (1 Mg/m³). Open porosity is given by the portion of open pores which are connected in the rocks and can be filled by water. The gas permeability was measured by the steady state method. Ultrasonic wave velocity (both P- and S-waves) was measured with ultrasonic pulse transmission technique. The values of travel time (\(t_p\) and \(t_s\)) were calculated using the time cursor on the oscillogram. The velocities were calculated from the core length and the travel time measurement using the formula: velocity = core length/travel time. The frequency of transducers was 1 MHz for dense samples and 250 kHz for porous samples. The measurements were done in dry as well as in water-saturated states.

The uniaxial compression test was performed on an universal testing machine Controls 1500 kN. Uniaxial compressive strength was determined for samples in dry and water-saturated states. Then, the softening coefficient (\(C_{swt}\)) was calculated as the ratio between strength values in water-saturated and dry states. The elastic constants were calculated from the measured wave velocities and the bulk density. Friction angle (\(\phi\)) and cohesion (C) were calculated from Mohr–Coulomb diagram through uniaxial compressive and tensile strength.

Special testing was made for hydrothermal clayey soils. The following properties were determined: in-situ moisture content, hygroscopic moisture, plasticity, and swelling. Mechanical properties included shear strength parameters (friction angle \(\phi\) and cohesion C) which were defined from direct shear test in undrained conditions.

All samples were studied petrographically (optical microscope “Olympus” BX-41). Secondary minerals were also identified using X-ray diffraction (DRON-3). Bulk analyses were carried out, and then analysis of clay-size fraction (less than 2 micron) was performed on a portion of the samples to obtain precise clay mineral composition. Microprobe analysis was conducted for a portion of the samples (electron microscopes Camebax SX-50 and LEO 1450VP with microprobe apparatus INCA 300) to study the morphology of pore space and chemical alteration that occurred during the hydrothermal process. Pore space morphology was studied with x-ray micro-computed tomography (Yamato TDM-1000, Japan).

4 HYDROTHERMAL ALTERATION AND MECHANICAL PROPERTIES

In the Low-Koshelevsky thermal field andesites are exposed in the surface. Under the action of fluids (with pH = 3.5–5.5; T up to 95–100°C, Rychagov et al. 2008) they are gradually destroyed and transformed into clays. Alteration starts in fracture networks exposed to thermal water and steam. The walls of fractures are rapidly replaced by clay minerals.

Gradually the fractures propagate and expand, and new blocks of andesite are altered by argillization. In the end only cores of andesites (which are intensely fractured, ferruginized, and argillized) remain surrounded by a clayey mass. It can be assumed that the progressive fracturing occurs under the pressure of swelling in the surrounding clay mass. Thus, the clay mass is very heterogeneous, and contains hard relics of andesites. The clay soil is mainly smectite or mixed-layer minerals with some silica minerals and occasionally pyrite. It has pseudomorphic texture inherited from andesite.

Alteration process is followed by leaching with formation of secondary pores in the rock matrix and than the initiation of microcracks. It is clearly seen in images from micro-computed tomography (Fig. 2).
Figure 2. Change of space-morphology of andesites (tomography data). Top – fresh andesite with massive structure, middle – moderately altered andesite with secondary pores; bottom – intensely altered andesite with microcracks.

Figure 3. SEM images. Smectite replaces volcanic glass. Top – the first “leaves” or “scales” of smectite develop by volcanic glass; middle – “scaly” smectite; bottom – cellular smectite.

Electron microscopy has shown that dense volcanic glass is replaced by cristobalite and porous smectites (mixed-layers), firstly with scaly and then with cellular microstructure, that reflects on rock properties (Fig. 3). Subsequently the microcrysts in the groundmass are partially dissolved.

Alteration of plagioclase phenocrysts basically begins from microcracks and flaws. Then, the inner (central) part of the crystal, which is more anorthic or andesine composition is replaced, whereas the outer part of the crystal (more albite composition) is more
stable to alteration and succumbs to alteration at later stages (Fig. 4). This fact is confirmed by microprobe investigation in electron microscope (Fig. 5). Finally the crystal can be totally substituted but it maintains its initial shape.

Hydrothermal alteration effects on rocks physical and mechanical properties. By the intensity of alteration the studied andesites are subdivided on fresh or slightly altered, moderately, and intensely altered. Intensity of alteration correlates with the temperature of thermal fluids (70°C for slightly altered, 84–92°C for moderately altered, and 95–100°C for intensely altered).

Alteration processes results in mechanically weaker rock. Development of smectite-filled microcracks (content of smectites is up to 28–32%) decreases density of andesite from 2.6 to 2.1 Mg/m³, and increases porosity from 2–5 to 25–30%. As a result uniaxial compressive strength decreases from 130–150 (fresh andesites) to 25–30 MPa (intensely altered andesites), velocity of the P-wave changes from 4.5–5.0 to 2.5–3.5 km/s. Dynamic elastic modulus decreases from 50–55 to 15–20 GPa and static modulus is approximately 2–2.5 times less than dynamic. Figure 6 shows the relationship between properties and intensity of alteration for andesites from trial pit NK-1/10.

The saturation of rocks with water influences in different way for fresh and altered andesites. Strength is almost the same in dry and saturated states for unaltered andesite whereas it decreases by 40% due to saturation for intensely altered andesite. So high content of smectite causes rock softening in saturated state.

The total transformation of andesites to clays is accompanied by a strong reduction in dry density (fresh andesites 2.5–2.6 Mg/m³, clays 1.0–1.1 Mg/m³), increase in porosity (from 2–8% to 61–63%) and hygroscopicity. Cohesion decreases from 15–20 MPa (andesites) to 0.02–0.05 MPa (clays) and friction angle changes from 55–57° (andesites) down to 10–21° (clays). Hydrothermal clays are characterized by high plasticity (plasticity index equal to 29–30) and slightly swelling. In-situ they belong to the stiff clays.

5 CONCLUSION

Geothermal areas are basically located within volcanic formations. At geothermal fields volcanic rocks
interact with thermal water and steam and gradually transform in clayey soils, which can be the foundation for power plants construction and affect the selection of sites and design for buildings and pipelines. Alteration processes result in strong decrease in density and mechanical properties which correlate with intensity of alteration. The cover of hydrothermal clays is a very heterogeneous horizon characterized by high porosity, plasticity, hygroscopicity, increased weakness, softening and occasionally swelling in saturated state.

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REFERENCES


Figure 6. Changes of andesite properties due to argillization. From the top to the bottom: bulk density, porosity, uniaxial compressive strength, dynamic elastic modulus (data from trial pit NK1/10).