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The Impact of Hydrothermal Activity on the Geological Environment, Kamchatka Peninsula

Julia V. Frolova[1], Michael S. Chernov[1], Sergey N. Rychagov[2], Oleg V. Zerkal[1]

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

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

ju_frolova@mail.ru

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ABSTRACT

Geothermal exploration and development of geothermal sites requires the investigation of their engineering geological setting and an assessment of the hydrothermal activity impact on the environment. Hydrothermal alteration of rocks and changing in their physical-mechanical properties promotes a broad range of geological phenomena that is indicated by many researchers on various geothermal sites all over the world. There are slope instability with the initialization of landslides or rock avalanches, changes in relief, hydrothermal explosions, migration of thermal manifestations, changes in temperature and the hydrodynamic regime of a hydrothermal system, reduction of well production, surface deformation and subsidence, discharge of wastewater from production wells to the creeks with formation of silica deposits etc. These processes have an impact on the environment and influence on exploitation of the geothermal field, and in some cases, they could be hazardous for the economic or tourist development of the geothermal site. In the paper we discuss the environmental impact problems induced by hydrothermal activity, which may occurred during natural evolution of hydrothermal systems or due to the geothermal development and utilization, and describe the geological phenomena associated with hydrothermal activity on the most well-known hydrothermal systems of Kamchatka Peninsula (Far East, Russia).

1. INTRODUCTION

Geothermal exploration and development of geothermal sites requires the investigation of their engineering geological setting, including hydrothermal alteration and an assessment of the hydrothermal activity impact on the environment. Progressive hydrothermal alteration of rocks and changing the physical-mechanical properties promotes a broad range of geological phenomena that is indicated by many researchers. There are instability and failure of slopes with the initialization of landslides or rock avalanches, hydrothermal explosions, surface deformations etc. These processes have an impact on the development and exploitation of the geothermal field, and in some cases, they could be hazardous for the economic or tourist development of the geothermal site.

Hydrothermal eruptions are common phenomena in geothermal fields that is noted in papers of Hedengvist and Henley (1985), Lawless and Browne (2001), Handal (2004), Montanaro et al. (2015), Shulyupin et al (2016). They can be natural events due to evolution of hydrothermal system or had artificial origin induced by geothermal exploration. They took place in prehistoric or historic times. Geological product of hydrothermal eruption is breccia or brecciated rocks. After the eruption, secondary minerals deposited from the filtering fluids quickly cement the formed debris. Lawless and Browne (2001) insisted that many hydrothermal eruptions start close to the ground surface and result from the rapid formation of steam due to a sudden pressure reduction. This steam provides the energy necessary to brecciate, lift and eject fragments of the host rocks as a flashing front descends and water nearby in the reservoir boils. A hydrothermal eruption continues until the steam is produced too slowly to lift the brecciated rocks. There is no genetic difference between the small eruptions induced by exploitation and those, which occur as a geothermal system evolves naturally and whose effects may penetrate to much greater depths.

Lawless and Browne (2001) summarized data about hydrothermal eruptions in New Zealand but also mentioned examples all over the world. They justified the importance of studying hydrothermal explosions. The main reason is that they are destructive events that can cause human victims loss and damage or destroy structures of geothermal plants and pipelines. The information about prehistoric events and eruptions frequency will assist to avoid potentially dangerous sites when planning pipelines, power plants, and reinjection systems. The second reason is that hydrothermal eruptions may cause major changes in the hydrogeological structure of the hydrothermal system and thus influence on production regime and volume. The third reason has scientific importance. The material ejected by a hydrothermal eruption provides knowledge about the lithology of the geothermal reservoir from which it derives. In addition, hydrothermal minerals, which cement debris in breccia, bring information about the subsurface conditions such as temperatures, fluid types and salinities. One more reason is that hydrothermal breccia can be the host rocks for epithermal mineral and ore deposits.

Slope processes are widespread in geothermal areas. They are often hazardous for the economic, social and tourist development of the regions that mentions by Reid et al. (2001) and Suemnicht et al. (2007) for Long Valley caldera, USA; Huang and Tian (2006) for geothermal fields in China; Dvigalo and Melekestsev (2009), Kiryukhin (2010, 2012), Gvozdeva et al. (2015), Zerkal and Gvozdeva (2018), Zerkal et al. (2019) for Geysers Valley on Kamchatka, Russia; Pioquinto and Caranto (2005), Pioquinto et al. (2010) for Philippines; Kristianto et al. (2013), Wijaya et al. (2014), Yuhendar et al. (2016) for Indonesia; Della Seta et al. (2015), Marmoni et al. (2017) for Ischia Island, Italy.

A significant impact to the study of the catastrophic slope processes in geothermal areas was given by a landslide of more than 800 thousand m^3, formed in 1991 on the Zunil I hydrothermal field (Western Guatemala), which operated 10.8 MW power plants that described by Flynn et al. (1991) and Voight (1992). Twenty-three people were killed in this landslide; several farms were destructed.

Wijaya et al. (2014) considers a landslide disrupted the operation of the reinjection well in the geothermal area Kamojang (West Java, Indonesia) in 2013. The landslide of 33 thousand m^3 was formed in hydrothermally argillized andesites. The mechanism of the movement was complex: slip landslide transformed to earth-flow. The sliding surface was confined to the horizon of hydrothermal clay soils. Twenty-eight landslides formed in hydrothermally altered volcanic rocks were recorded in this geothermal area.

Suemnicht with co-authors (2007) showed the correlation between landslides, hydrothermal alteration of rocks and the structure of the shallow hydrothermal system for Long Valley caldera (California, USA). Hydrothermal process weakened the slopes within the calderas due to intense argillization of volcanic rocks. The landslide was formed on a site where the thermal waters of a deep-seated hydrothermal system discharged along a ring fault controlling the position of the caldera scarp. The impermeable landslide block and intensely altered clay-rich horizon of the tuff separate the shallow hydrothermal reservoir from deep cold recharge.

Ischia Island (Italy) experienced slope instabilities during the Holocene that occurred at different scales, from shallow mass movements up to large rock and debris avalanches as described by Della Seta et al. (2015) and Marmoni et al. (2017). These events were strictly related to volcano-tectonic process as well as intense hydrothermal activity, leading to the alteration of tuffaceous rocks and a decrease in their strength and deformation properties.

Huang and Tian (2006) consider the geological hazards such as landslide, rock fall, and other types of slope failure that are spread in the hydrothermal alteration zones of high-temperature geothermal regions in China.

Pioquinto and Caranto (2005) describe landslides and slope failure hazards, which are common phenomenon in geothermal fields in Philippines. One of the triggering factors is the presence of hydrothermal weak clay-rich soils and also fumaroles and mud pools above the slopes. These landslides had a damage for pipelines, roads and buildings of the power plants. The authors offer the hazard assessment methodology and consider the engineering measures to mitigate the impact of landslides.

Surface deformations are often observed in geothermal areas. They can be caused both by natural processes during the evolution of the hydrothermal system, or by exploitation of geothermal field. It can various movements such as subsidence, uplift or fluctuations of the surface.

On the one hand, many researchers note that long-term surface deformation often occurs in calderas as natural process without any connection with development of a geothermal field (Rouwet et al., 2014). It also does not connect with volcanic eruptions or magma migration (the examples are Rabaul, Papua New Guinea; Long Valley caldera; "supervolcano" Yellowstone, USA; the Campi Flegrei caldera, Italy). Hydrothermal process is considered as one of the main reason, which causes surface deformation (Rouwet et al., 2014). For example, the discussion about deformation in the highly populated Campi Flegrei caldera has been ongoing since the 1980's. Recently, the tendency to explain the uplift by the expansion of the underlying hydrothermal system has become more popular as it is supported by decade-long monitoring time series (geochemistry, geodesy, geophysical surveys). The Campi Flegrei deformation is considered an example of prolonged hydrothermal non-eruptive unrest, manifested as ground deformation paired with diffuse degassing.

On the other hand, the surface subsidence is one of the geological hazards occurred during the development and exploitation of geothermal fields that is mentioned by Samsonov et al. (2001), Huang and Tian (2006), Sarychikhina et al. (2011). Koros et al. (2015), White et al. (2015). Sarychikhina et al. (2011) notes that the economic and environmental impact of land subsidence can be substantial. It can destroy surface drainage, reduce aquifer system storage, create ground fissures and cause damage to properties, farmlands, and infrastructure that may be costly to replace or repair. White et al. (2015) generalizes data about surface deformation and declares that subsidence due to exploitation has been documented at many geothermal fields all over the world, including the Geysers, Svartsengi, Cerro Prieto, and Wairakei-Tauhara.

One of the examples is the Cerro Prieto geothermal field in Mexico. The large amount of geothermal fluids extracted to supply steam to the power plants has resulted in considerable deformation in and around the field. The deformation includes land subsidence and related ground fissuring and faulting. These phenomena have produced severe damages to the local infrastructure such as roads, irrigation canals and other facilities that is described in the paper of Sarychihina et al. (2011).

Another example is the Wairakei geothermal field in New Zealand, where subsidence has occurred since the beginning of production in the 1950's. Koros et al. (2015) describes that subsidence rates increased from the 1950s to a peak in 1970s, followed by a decline to much lower rates at present. In the most profound subsidence area, the peak rate was 498 mm/year in 1978. This has now reduced to a current rate of 58 mm/year. The center of the Wairakei subsidence bowl has dropped by a total of approximately 15.1 m since the 1950s. The total area of the subsidence bowl covers approximately one km^2.

In addition to the main processes mentioned above, there is a wide range of other processes and phenomena, taking place in the geothermal regions. There are migration of thermal manifestations and changes in their regime, reduction of well production due to exploitation, changes of landscape features, etc.

The aim of the paper is to discuss the environmental impact problems induced by hydrothermal activity, which may occurred during natural evolution of hydrothermal systems or due to the geothermal development and utilization, and to describe the geological phenomena associated with hydrothermal activity on the most well-known hydrothermal systems of Kamchatka Peninsula (Far East, Russia).

2. GEOLOGICAL SETTING

The main geothermal heat and energy resources in Russia occur in the Kuril–Kamchatka volcanic arc, which is located in the northwestern segment of the Circum-Pacific Belt. This area is situated above a subduction zone and is characterized by active volcanism and geothermal activity. Tens of low- and high-temperature hydrothermal systems are located in the region. Several geothermal electric power plants (GeoPP) are operating there (Mutnovsky and Pauzhetsky GeoPP, and small power plants on the Kurils). Some fields are used for space heating, recreation and green houses. Most geothermal areas are confined to the slopes of Quaternary volcanoes or located within calderas. The host rocks of hydrothermal systems are volcanic or volcaniclastic formations of Neogene–Quaternary age. The rocks are intensely altered under the action of thermal fluids and partially transformed to hydrothermal-metasomatic rocks such as propylites, zeolitic rocks, argillic rocks, secondary quartzites, opalites, and quartz–feldspar metasomatites. The location of the studied hydrothermal systems is shown in Fig. 1, and a brief description of their geological features is given below. Detail geology is described in books of Belousov and Sugrobov (1976), and Rychagov et al. (1993).

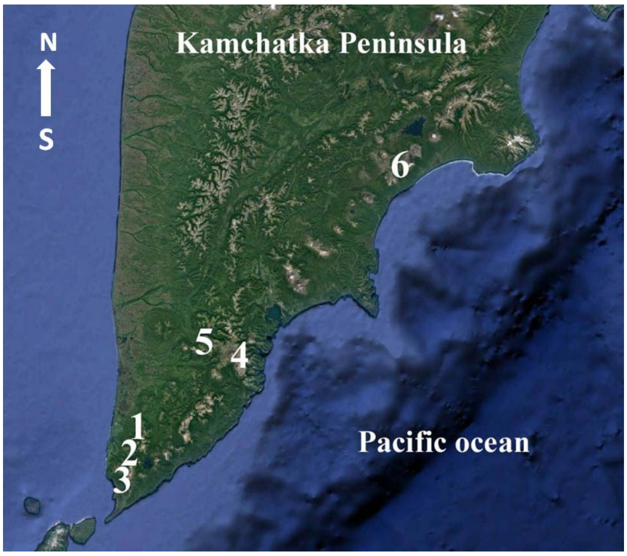

Figure 1: The Location of studied hydrothermal systems. Hydrothermal systems: 1 – Pauzhetsky, 2 – Kambalny, 3 – Koshelevsky, 4 – Mutnovsky, 5 – Bolshebanny, 6 – Geysers Valley

2. THE IMPACT OF HYDROTHERMAL ACTIVITY ON THE GEOLOGICAL ENVIRONMENT ON DIFFERENT HYDROTHERMAL SYSTEM

2.1 Pauzhetsky hydrothermal system

The 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. The extensively studied Pauzhetsky hydrothermal system is situated on the slope of Kambalny Ridge inside the depression. The first geothermal power plant in the USSR has been operating there since 1967. Presently the installed capacity of Pauzhetskaya GeoPP is estimated as 11 MW_e. The hydrothermal system is hosted in Neogene–Pleistocene tuffs alternating with lava flows and intersected by dykes. Thermal fluids with the temperature up to 180–200°C intensely alter the rocks. The following alteration zones are distinguished from the surface down to 600 m depth: argillic, zeolitic, and propylites. Quartz-adularia metasomatites are developed in some fault structures. It is suggested that the system is in a regressive stage of development as seen by a low-temperature mineral assemblage superimposing a high-temperature one (Rychagov et al., 2005). The system is liquid-dominated where the main reservoir is found in highly permeable zeolitized lapilli tuffs. The caprock consists of argillized ash vitric tuffs. Due to the discharge of heat, transported by the steam-water flux in the subvertical faults, several thermal fields are formed on the surface, covered by clay-rich soils.

2.1.1 Hydrothermal eruptions

Hydrothermal eruptions can be recognized from the presence of eruption breccias. These rocks are formed under particular thermodynamic and geochemical conditions, which are characterized by a fluid flashing i.e. transition from liquid phase to steam due to sudden pressure reduction. The fluid flashing and boiling cause a temperature decrease, heat loss, gas release, and increase of pH. These conditions are favorable for formation of quartz-feldspar metasomatic breccias. Quartz-feldspar metasomatic breccias were met in cores of several boreholes form different depth (25-150 m). Breccias consist of large debris of hosted tuffs cemented by fine crystalline quartz and adularia. The debris of initial tuffs are altered and substituted by quartz, adularia and wairakite; epidote and prehnite occasionally occur. Cracks of hydraulic fracturing filled with quartz are found in the rock. In general, the metasomatic breccias are dense (2.0-2.5 g/cm^3) and mechanically strong (compressive strength is about 80-170 MPa) due to quartz cementation, but they contain rather large cavities formed by leaching, so porosity of rocks can reach 30-35%. In book of Rychagov et al. (1993) these rocks are considered as deposits of fault or intensely fractured zones in which fluid flashes at certain depth, but not as the products of hydrothermal eruptions. Therefore, this question requires more careful studying.

A small hydrothermal explosion occurred while working on the East Pauzhetsky thermal field in 2018. In the process of drilling, there was a sharp release of hot steam with ejected fragments of the host andesites. Apparently, the drill came into the overheated steam zone in fractured andesites, covered with insulating horizon of hydrothermal clays. After the eruption, large mud boiling pool was formed on this place (Fig.2).

2.1.2 Disposal thermal water and silica deposits

Steam from production wells is separated from the water and is then used to power a turbine/generator unit. The waste thermal water (pH~8.5, T≤100°C) is directly disposed of into the creeks results in formation of thick layer of special silica deposits on the bed (Fig.2). Generally, vertical section of deposits is composed from three layers. The uppermost layer of thermophile blue-green alga is underlain by silica-gel layer (~ 15-20 cm). The lower layer is composed of solid silica material. The cover of silica deposit has several hundred meters length, tens meters width and about 0.5-1.0 m thick (Frolova et al., 2006).

Figure 2: Some examples of hydrothermal impact on environment in Pauzhetsky hydrothermal system. Left: Mud boiling pool, formed after hydrothermal eruption during drilling (photo is submitted by IV&S RAS, October 2018). Right: Silica deposits in the creek precipitated form waste thermal water.

2.1.3 Migration of thermal manifestation and regime change due to geothermal exploitation

Averiev and Sugrobova (1965) studied the distribution and regime of natural thermal manifestations in natural conditions and during one year of exploration. They indicated a change in regime of thermal springs during the first tests of geothermal exploration. During exploration, some thermal springs noticeably reduced the flow rate, and some disappeared. In particular, two geysers located on the floodplain of the river changed their regime. At the same time new steam vents and mud pools were formed. When the operation tests were stopped there was a rapid recovery of the static level of thermal waters and the flow rates of the thermal springs reached their original values. Geysers have restored their original regime. Mud pots and steam vents caused by well operation have disappeared. It was concluded about the interrelation between natural springs and production wells. Later, during the operation of the thermal field, the geysers disappeared.

2.2 Kambalny hydrothermal system

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 at 18–20 km. We studied one of the field in the South-Kambalny group. This part of the ridge is a complex stratovolcano (Q_{2-3}) 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 andesites or basaltic andesites. The 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. Successive stages of hydrothermal alteration are distinguished on the 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 compose 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.

Progressive hydrothermal alteration of andesites and changing in their mechanical properties promotes a broad range of geological phenomena including slopes instability with the initialization of landslides, migration of thermal manifestations, changing in landscape. It was noted that many shallow landslides affect slopes of the valley. Weak argillized rocks and clay-rich soils slides on hard basement forming slides or creeps (Fig.3). It was also observed that thermal manifestations change their location during the time. This is evident from the fact that the fields of altered rocks often do not coincide with the present discharges of thermal water and steam. It is clearly seen for opalites and quartzites, which compose elevated sites on the thermal field in places where there is currently no thermal manifestations.

2.3 Koshelevsky hydrothermal system

Koshelevsky hydrothermal system occupies the most southern position on Kamchatka Peninsula, located on the slope of a volcano of the same name. It is a high temperature system with temperature reaches 260°C at the depths of 1100 m. Host rocks are volcanic and volcaniclastic types of Neogene-Quaternary age. There are two main thermal fields (Low- and Upper-Koshelevsky) with different temperature and fluid composition.

The Low-Koshelevsky field is located on the slope of volcano at an altitude of 750–800 m in an erosion depression 250×500 m^2 in size. Total heat discharge is about 24,800 kcal/s. There are numerous gas-steam vents, boiling and pulsatory springs and mud pools. Thermal waters are predominantly slightly acidic sulphate and hydrocarbonate-sulphate composition (pH=3.5-5.5, temperature is up to 90-97°C). The thermal field is formed on andesites, which are gradually transformed into hydrothermal clay-rich soils. Alteration starts in fractures exposed to thermal fluid. The walls of fractures are rapidly replaced by clay minerals. Gradually the fractures propagate and expand, and new blocks of andesite are altered though argillization. Finally, only relicts of andesites remain in surrounded clayey mass. Thus, the clay layer is very heterogeneous, and contains relicts of andesites. The composition of clays is mainly smectites or mixed-layer minerals. Transformation of andesites into clay-rich soils is accompanied by drastic decompression (andesites 2.5-2.6 g/cm^3, clay soils 1.0-1.1 g/cm^3), an increase of porosity in 10 times (from 5-8% to 50-60%), and a decrease in shear strength in 2-3 orders. Water impregnation softens the clay and increases plasticity. Transformation of hard andesites to soft clay-rich soils promotes slope instability and leads to formation of landslides (Fig.3). Hydrothermal alteration of rocks and permanent sliding of the weaken slopes promotes to formation of erosion depression.

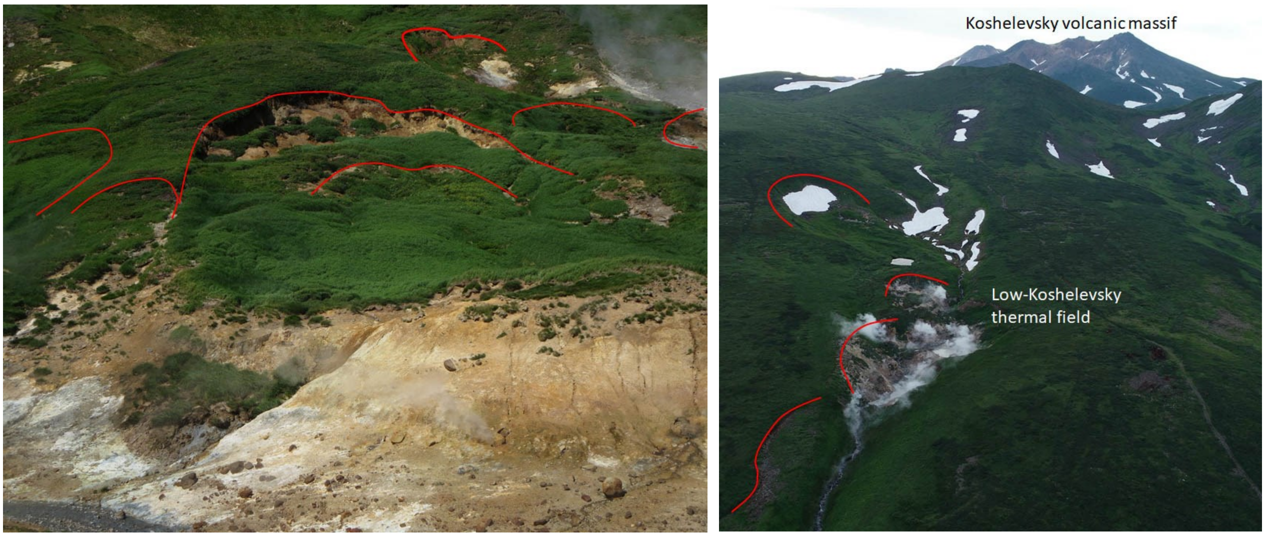

Figure 3: Shallow landslides in hydrothermal clay-rich soils on South-Kambalny (left) and Low-Koshelevsky (right) fields

2.4 Mutnovsky hydrothermal system

It is one of prospective and the best studied geothermal fields. It is situated approximately 70–80 km south of Petropavlovsk-Kamchatsky city. The region has been the site of extensive drilling for geothermal development since the middle of the 1970s. Two geothermal power plants are presently under operation with installed capacities of 12 and 50 MW_e; they supply electricity into the power grid of the Kamchatka Peninsula. This is a high enthalpy system with temperature of fluid up to 280°C. It is assumed that the system is fracture-dominated where the main production zone coincides with a fault. The dominant stratigraphy in the geothermal system consists of a complex volcanic sequence of Oligocene–Miocene to Holocene age. It consists of tuffs, tuffites, breccias, andesites, basaltic andesites, dacites, and ignimbrites. The entire geological section is intensely altered. The following alteration zones occur down to depths of 1000 m: sulfate acid leaching, argillic zone, low- and medium-temperature propylites.

2.4.1 Surface deformations

Kiryukhin with co-authors (2015) conducted the monitoring of vertical deformations on Mutnovsky volcano during 2004-2013. They identified three deformation areas with different transient vertical deformation regimes. The first area is located in the central part of the Dachny site, where some uplift (2–5 mm/year) was observed. The second area is located in North reinjection site and is characterized by surface fluctuations. There was no significant vertical deformation during 2003-2006, whereas some uplift (6–7 mm/year) took place during 2006–2008 followed by subsidence (5–8 mm/year) during 2009-2010. Finally, the third are is located on Verkhne-Mutnovsky site, where significant subsidence has been taking since 2008 at a rate of 6–18 mm/year. The authors suggested that variable deformations in different parts of the geothermal system can be caused by both natural factors (fault zone, magma migration) and exploitation of the thermal fields.

2.4.2 Landslides

Numerous landslides are observed on the slopes and in the crater of the Mutnovsky volcano. Different types of landslides can be distinguished such as deep-seated block slides, shallow earth flow (creep) in hydrothermal clays on the thermal fields, or rock avalanches and rock falls in the crater. In particular, earth flows or creeps are often formed on the thermal fields confined to the slopes of volcano. Moistened stratum of hydrothermal clays (several meters in thick), lying on a hard rocky basement, are involved in the viscoplastic movement. Especially dangerous are rock falls and landslides occurring at the entrance to the crater, in the place of the hiking trail.

2.5 Bolshebanny hydrothermal system

The hydrothermal system is located 65-70 km to the west-south-west of Petropavlovsk-Kamchatsky city. At present, the interest of geologists to the Bolshebanny hydrothermal system has resumed due to the development of tourism in this site. The area is composed of volcanogenic deposits of Neogene-Quaternary age. The rocks have very contrast composition and represented by basalts, andesites, dacites, rhyolites, tuffs, and ignimbrites. Bolshebanny thermal field is one of the largest and most known groups of thermal springs in Kamchatka. The filed is located at the northern foot of the volcanic massif Goryachaya Hill, mainly on the left side of the Bannaya River. Hot springs are traced along the river for about 1.5 km (total area is about 0.5 km^2). The water discharges are observed on the terraces, floodplain, and at the water edge. The water temperature in the springs ranges from 20-30 to 90-99°C. Water is sulphate-chloride-sodium composition with mineralization varying from 0.5 to 1.2-1.4 g/l. It is shown that a main role in the structure of the field is played by the northwestern direction faults, crossing the valley of the Bannaya River and substantially redistributing the flow of thermal water and steam raising from the depth. As a result, the thermal field is formed on the surface, elongated along the fault line of the north-west strike. The surface of the field is partially covered by highly porous silica deposits underlain by clayey soils.

Trukhin and Petrova (1976) compared the boundaries of modern hydrothermal activity (by isotherm 100°C) with the area of altered rocks and made a conclusion about migration of the thermal field in time. They considered three factors to explain migration of thermal manifestations. One of suggested reasons can be a change of fluid pathways due to hydrothermal alteration of rock with precipitation of secondary minerals in pores and cracks.

The surface of the field is characterized by a hilly relief, which was formed due to landslide processes (mostly creep) in spite of relatively gentle slope. It should be noted that the processes occurring on the thermal field are interrelated. The discharge of thermal waters causes rock alteration with the deterioration of their properties - both strength and permeability decrease. This leads, firstly, to the displacement of the rock mass, i.e. to the formation of a landslide, and secondly, to the closure of filtration paths due to a decrease in permeability. As a result, there is a change in the place of discharge of thermal waters.

2.6 The Valley of Geysers

The Valley of Geysers is located 180 km northeast of Petropavlovsk-Kamchatsky city within the Uzon-Geyser volcanic-tectonic depression, filled with volcanogenic sedimentary deposits of the Pleistocene age (East-Kamchatka volcanic belt). It belongs to the Kronotsky State Natural Biosphere Reserve and is included in the UNESCO World Natural Heritage Site "Volcanoes of Kamchatka". It is a very attractive touristic site with tens of geysers and other thermal manifestations. The valley of Geyzernaya River cuts the volcanic massif, which is mainly composed of Pleistocene tuffs and tuffites.

The structure of the Geyser hydrothermal system is an artesian slope. It is assumed that the heat source is a magma chamber of the volcano Kikhpinych. Deep-circulated waters heat up from the magma chamber and form an upward flow with a temperature of 250–330°C. Rising toward the surface, they are cooled by mixing with cold waters and the loss of steam, and transform to lateral flow with a temperature of 180°C. The main discharge occurs in the lower part of the Geysernaya River. By heat release, the Geysers Valley hydrothermal system is one of the most powerful in Kamchatka.

The hydrothermal system is hosted in pumice-rich tuffs and tuffites. Tuffs are highly porous, hygroscopic, weak, and unstable in water-saturated state. Physical-mechanical properties of tuffs are quite variable and depend mainly on rock primary features (composition, structure, and grain size) and degree of hydrothermal alteration. Two hydrothermal facies are distinguished in geological section: low-temperature propylites and hydrothermal argillites with high-silica zeolites. Propylitic tuffs are characterized by higher density, elastic modulus, and compressive strength in comparison with argillized tuffs. In some zones and on the surface tuffs are totally altered into clayey soils. Smectites are widespread in tuffs due to alteration of volcanic glass under the action of thermal water. They cause significant decrease of rock mechanical properties especially in water-saturated state. Thus, cohesion decreases by two orders and the angle of internal friction by 2-3 times.

2.6.1 Landslides, changes of landscape, changes of geysers regime

The Valley of Geysers is well known after the catastrophic landslide occurred in June 2007. By different estimations the landslide volume was about 16-21 million m^3 (Fig.4). The landslide was formed in the left side of the Geyzernaya River. The main scarp was about 50-60 m high. As a result of slope deformations a landslide tongue formed with about 1.5 km length and 0.2-0.4 km width. Grozdeva et al. (2015) reported that the main displacement was as viscoplastic flow of ground mass and continued during 2.5 minutes. Steaming blocks of hydrothermal clays were observed among landslide deposits.

After the slope failure, the zone of argilization was clearly seen in the scarp. We investigated the hosted rocks and landslides deposits in 2013 and concluded that tuffs were strongly argillized under the action of thermal water. In some faults or highly fractured zones, they totally transformed to clay soils that it greatly reduced the strength of rocks. Thus, intensive hydrothermal activity in combination with the spread of a thick stratum of argilized tuffs with horizons of hydrothermal clays created conditions for landslide activation.

The landslide completely changed the landscape, created a dammed lake, destroyed or changed the regime of a number of geysers, and only by happy chance did not lead to human victims. The landslide strongly changed the landscape. The Geyzernaya River was dammed up by landslide deposits with formation of dammed lake (dam thickness was 20-40 m, length was 300 m). Some of geysers lost under the water, several geysers changed their regime. Kiryukhin et al. (2015) described the results of hydrogeological regime monitoring in 2007-2013 on major geysers and springs following the disastrous landslide of 3.06.2007 and showed that their characteristics have undergone significant changes.

It should be noted that landslides are rather regular phenomenon in the valley. In particular, another large complex landslide was formed in 2014 upstream from the Valley of Geysers (Fig.4). It started as rock avalanche (or debris avalanche) and then transformed to debris flow. It blocked the river, creating a dam lake, and significantly influenced the regime of geysers. Small shallow landslides, earthflows, taluses, and debris flows are also widespread in the valley. They happened in the past and will happen in the future. Gvozdeva et al. (2015) reveled that disastrous failure of 2007 was formed within ancient landslide presently covered by vegetation.

The main factors promoting landslides in the Valley of Geysers are special geological conditions of the territory including lithology, tectonic faults, landscape (steep slopes of the valley), high seismicity, and climatic particularities such as abundant atmospheric precipitation and snow melting. Hydrothermal alteration of rocks appears to be additional contributing factor for landslide. Thermal water affects volcanic rocks and transforms them into argillized rocks and clay-rich soils that causes a drastic decrease in their physical and mechanical properties and controls slope stability. It is concluded that intensive hydrothermal activity combined with the presence of argilized tuffs and hydrothermal clays create conditions for further activation of landslide processes.

The processes occurring in the Valley of Geysers are interrelated. Hydrothermal alteration of rocks with weakening and reduction in strength leads to slope instability and the formation of landslides. Large landslides change the landscape, and dams the river. Rising water levels in the river leads to the formation of new landslides on the sides of the valley. The geysers change their regime in connection with water level in the lake. Some of thermal manifestations change their location as a result new rocks are involved in hydrothermal alteration around new thermal discharges.

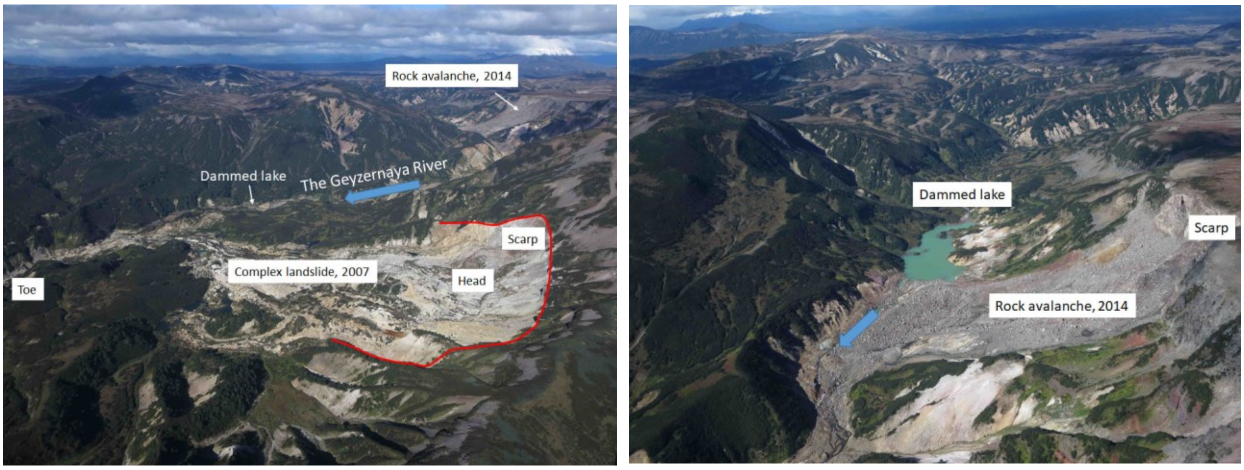

Figure 4: Landslides in the Valley of Geysers. Left: Complex landslide in 2007; Right: Rock avalanche and debris flow in 2014 (photos are made in 2016).

3. DISSCUSION

A broad range of geological phenomena is observed in geothermal areas at Kamchatka Peninsula. There are slope instability and landslides, changes in landscape, hydrothermal explosions, migration of thermal manifestations, changes in their temperature and the hydrodynamic regime, reduction of well production, surface deformation and subsidence, etc. In addition, discharge of thermal wastewater from production wells to the creeks leads to formation of silica deposits. These processes and phenomena may occurred during natural evolution of hydrothermal systems or due to the geothermal development and exploitation. In any case, they have an impact on the environment and influence on exploitation of the geothermal field, they can cause a damage of surface facilities as constructions of power plants, roads, pipelines, and in some cases, they can be dangerous for human lives. Table 1 shows geological processes and consequences induced by the hydrothermal activity on hydrothermal systems of Kamchatka Peninsula.

The landslide processes and phenomena are widespread in the geothermal regions at Kamchatka Peninsula. This is largely due to the fact, that geothermal areas are located in mountainous areas characterized by steep slopes and high seismicity. At the same time, landslide processes in geothermal regions have specific features of formation and mechanisms of development, which is caused firstly by the hydrodynamic effect of circulating thermal fluids within the hosted volcanic massif, and secondly by large-scale rock alteration that drastically decreases their physical-mechanical properties and leads to slope instability and failure. Hydrothermal alteration of rocks (first of all, argillization) often causes their decompression, formation of secondary porosity and fracturing, and a reduction in strength and deformation properties, down to the transformation of hard initial rocks into dispersed clay-rich soils. This is one of the main reasons for the stress redistribution in slope massif that contributes to activation of landslide processes of various types and scales.

In particular, slope processes of various types occur in thermal fields confined to slopes of volcanic massifs or the sides of river valleys. The most common are shallow earth flows or creeps, which are formed when moistened strata of hydrothermal clays (several meters in thickness), lying on a hard bedrock, are involved in viscoplastic movement. Rock and debris slides are also common. Surface of rapture often coincides with argillized rocks, characterized by a reduced strength and to which the horizons of thermal waters are confined. There are known the complex deep-seated large-scale landslides and rock avalanches, that are dangerous for economic or tourist development of geothermal fields. A striking example is the landslide in the Valley of Geysers, which occurred in 2007. It should be noted that thousands of tourists visit the Valley of Geysers every year. At the same time, it is one of the most dangerous place in Kamchatka due to intensive development of landslide processes, which occurred in the past and with a high probability, will occur in the future. Some measures should be taken to predict and mitigate landslide hazard. In addition to the Valley of Geysers, numerous landslides formed in hydrothermally altered volcanogenic rocks are also widespread in other geothermal regions of the Kamchatka Peninsula, for example, on the slopes and in the crater of the Mutnovsky volcano, in the valley of the Pauzhetka River, on the slopes of the Kambalny Ridge and the Koshelevsky Volcanic Massif, on the Bolshebanny thermal fields, and others.

Migration of thermal manifestations is observed on all studied thermal fields. This is clearly seen from the fact that the area of altered rocks often do not coincide with the discharge of thermal waters and steam. One of the reasons can be a closure of fluid pathways due to hydrothermal alteration of rock with precipitation of secondary minerals in pores and cracks. Variation of thermal manifestation regime in time is also typical for thermal fields. It should be caused both by endogenous or exogenous factors.

The different-scale changes in landscape are characteristic for studied thermal fields. There are erosion depressions formed due to hydrothermal activity, bumpy surface induced by creep of clay-rich soils on the slope, or large disturbances formed after large-scale landslides.

It should be emphasized that the processes and phenomena arising from hydrothermal activity are interconnected and represent a single sequence. Hydrothermal alteration of rocks causes rock weakening and reduction in strength that finally leads to slope instability and formation of landslides. Slope deformation and failure changes the landscape that can reflect on thermal manifestation regime and location.

Table 1: Geological processes and consequences induced by the hydrothermal activity on hydrothermal systems of Kamchatka Peninsula.

№	Hydrothermal system	Geological processes	Hydrothermal alteration on subsurface horizons and on the thermal fields
1	Pauzhetsky	Hydrothermal eruptions Formation of silica covers from waste thermal water Changes of hydrothermal manifestation regime	Argillized tuffs and andesites (smectites, high-silica zeolites, silica oxides) Clay-rich soils at thermal fields (smectite is prevail; kaolinite is in smaller amount)
2	Kambalny	Landslides Change of landscape features Migration of hydrothermal manifestations	Argillized basaltic andesites Clay-rich soils, opalites and secondary quartzites at thermal fields
3	Koshelevsky	Landslides Change of landscape features Migration of hydrothermal manifestations	Argillized and opalized andesites Clay-rich soils at Low-Koshelevsky field (smectites) Opalites at Upper-Koshelevsky field (silica oxides, kaolinite, alunite)
4	Mutnovsky	Landslides: shallow earth flow (creep), block slides, rock avalanches and rock fall Hydrothermal eruptions Change of landscape features Surface deformation and subsidence (Kiryukhin et al., 2015) Reduction of well production (Chernev, 2005)	Argillized and opalized tuffs Clay-rich soils and opalites at ancient and active thermal fields
5	Bolshebanny	Small shallow landslides (creep) Change of landscape features Migration of thermal manifestations and changes of their regime (Trukhin and Petrova, 1976)	Argillized volcanic rocks Clay-rich soils and porous geyserites at thermal field
6	Geysers Valley	Hazard slope instability: complex landslide, small shallow earth flow (creep), rock avalanche, debris flow Change of landscape features, formation of dammed lake Change of geysers regime (Kiryukhin et al., 2015)	Argillized high-porous pumice tuffs (smectites, high-silica zeolites, silica oxides) Clay-rich soils and geyserites at thermal fields

4. CONCLUSION

Hydrothermal activity, alteration of rocks and changing in their physical-mechanical properties promote a broad range of geological phenomena such as slope instability and failure with the initialization of landslides, changes in landscape, hydrothermal explosions, migration of thermal manifestations, changes in temperature and the hydrodynamic regime of a hydrothermal system, reduction of well production, surface deformation and subsidence etc. These processes and phenomenon may occurred during natural evolution of hydrothermal systems or due to the geothermal development and utilization. In any case, they have an impact on the environment and influence on exploitation of the geothermal field. In some cases, they can be hazardous that should be taken into account in the economic or tourist development of the territory. It should be emphasized that the processes and phenomena arising from hydrothermal activity are often interconnected and represent a single sequence.

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