Accumulative landforms in valleys with gas-hydrothermal manifestations of the Kuril-Kamchatka region

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Abstract. Within the watercourse valleys of geothermal zones, where manifestations of gas-hydrothermal activity are noted, the processes of relief formation are accompanied by chemical and thermal effects. Thermal waters contribute to the formation of specific accumulative landforms both directly in the channel and in the bottom and on the sides of river valleys. Similar phenomena have been studied in river valleys draining the slopes of the Mendeleev volcano (Kunashir Island), Baransky volcano (Iturup Island), Mutnovsky volcano and Uzon-Geyzernaya caldera (Kamchatka). The typification of accumulative relief forms is carried out, the influence of gas-hydrothermal manifestations on fluvial and slope processes is determined.

1. Introduction
In the river valleys of the geothermal zones of the territories of modern volcanism, there are often areas of active gas-hydrothermal manifestations that accompany volcanic activity, but can also persist after its attenuation. The locations of the outlets of thermal waters and solfataras within the volcanic edifices are usually determined by systems of radial and ring faults. River valleys on the slopes of volcanoes and at their feet are also usually confined to fault zones; therefore, gas-hydrothermal manifestations are often observed in the bottoms of erosional gullies and valleys. To date, few works have been published on the structure and development of such valleys; the influence of gas-hydrothermal waters on the formation of fluvial relief has been poorly studied. The purpose of these studies is to use the example of valleys on the slopes of several volcanoes in the Kuril-Kamchatka region to classify the forms of accumulative relief in the conditions of manifestations of gas-hydrothermal activity, as well as to determine the influence of the latter on the features of geomorphological processes in the valleys.

2. Methodology
The study is based on the results of field observations, sampling of alluvial and sinter sediments, waters of thermal springs and mud pots in the watercourse valleys on the slopes of the Baransky volcano (Iturup Island), Mendeleev volcano (Kunashir Island), as well as in the basins of rivers Falshivaya (slopes of the Mutnovsky volcano), Shumnaya and Geyzernaya (Uzon-Geyzernaya caldera) in Kamchatka. Analyzes were carried out in the laboratories of the IEC SB RAS (Irkutsk), FEGI FEB RAS (Vladivostok), POI FEB RAS (Vladivostok), «Primorgeologiya» (Vladivostok), IVS FEB RAS (Petropavlovsk-Kamchatsky) and IMGG FEB RAS (Yuzhno-Sakhalinsk).
3. Results

The formation and compositional characteristics of gas hydrotherms in volcanic areas, including the Kuril-Kamchatka region, have long attracted the attention of researchers and are widely discussed [1–10]. Gas-hydrothermal manifestations of the studied region include steam-gas outlets (mainly solfataras), mud pots and thermal springs (figure 1). In areas of high level of gas-hydrothermal activity, in the so-called solfataras fields, as a rule, carbonic, sulfate hydrothermal fluids with a complex cationic composition, having an average temperature of 80–100 °C, are observed. With distance from the center of volcanic edifices and the extinction of volcanic activity, thermal springs of various physical and chemical properties are encountered.

Figure 1. The geographical position of the Kuril-Kamchatka region (a); solfata of the Mendeleev volcano, Kunashir Island (b); mud pot in the valley of the Geyzernaya river, Uzon-Geyzernaya caldera, Kamchatka (c); thermal springs in the Kipyashchaya river, Baransky volcano, Iturup Island (d).

3.1. Typification of accumulative landforms in the watercourse valleys with gas-hydrothermal manifestations

Often, watercourses draining the slopes of volcanoes originate from the solfataras fields or cross them. Thus, within the limits of valleys, not only outlets of thermal waters, but also solfataras and mud pots can be observed. Therefore, we can distinguish several groups of landforms, which owe their appearance mainly to steam-gas outlets, or to the springs of thermal waters of various composition, as well as their specific interaction with the bedrocks.

3.1.1. Landforms associated with steam-gas outlets. The formation of sublimates in the form of deposits of native sulfur occurs around the solfataras. The composition of solfataras gases is predominantly carbon dioxide (more than 90 %), with some content of \( \text{SO}_2, \text{H}_2\text{S}, \text{HCl} \), etc. Precipitation occurs as a result of a sharp decrease in temperature and pressure, specific cone-shaped structures are formed around long-lived solfataras (figure 1, b), the height of which sometimes reaches 1–2 meters, and the average diameter is up to 1–2 m and more.

3.1.2. Landforms associated with the activity of mud pots. Mud pots are funnels and small basins (usually the first meters in diameter) filled with a liquid clay mass (figure 1, c). The chemical
composition of the water from squeezed mud mass is, as a rule, similar to the composition of the waters of the surrounding thermal springs. Acidic or slightly acidic sulphate mud pots with a mud mass temperature of up to 100 °C are most commonly found in solfatara fields and thermal sites [7, 9, 11, 12]. They are often located on the floodplain, and therefore, the removal of clay material by water flows can be observed there during floods or the rainy seasons.

In some cases, they are confined to the low terraces of streams, but, for example, in the valley of the river Geyzernaya, they are located on a terrace-like surface with elevations of about 30 m above the river. Usually mud pots, the diameter of which ranges from 0.5 to 3–5 m, are framed by the ring of mud material a few tens of cm high and up to 0.5–1.5 m wide; sometimes along their periphery, tongues of clay masses with a length of a few meters, less often tens of them, can be traced. In some areas near the pots, there are small groups of small «mud volcanoes» with a cone height of 20–30 cm.

3.1.3. Landforms created with the participation of thermal springs. Three types of accumulative formations associated with the inflow of mineralized waters into the streams are confined directly to the river channels: channel troughs, festoons and armored steps of waterfalls. All of them are formed in the areas of rapids, where water is saturated with oxygen, and the transition of soluble compounds into an insoluble form occurs and they precipitate. The same can be observed at other geochemical barriers: when streams merge or flow into water bodies with a different chemical composition of water. All this also leads to the formation of dense crusts in the channel and on the surfaces of the floodplain and terraces, to the cementation of alluvial deposits.

The most widespread microrelief forms are channel troughs – gutter-like sections of the channel formed by layered formations on rapids and in areas of narrowing. Their length is a few meters, and their width is from 0.2 to 1.0 m. They were found in almost all valleys of the studied watercourses with hydrothermal manifestations. The results of the analyzes have shown that they can be composed mainly of silica (SiO$_2$ 36–74 %), and oxides and hydroxides of Fe and Mn (up to 30 % or more), sometimes carbonates. Festoons are platforms of 0.4–0.7 m, often with a rounded edge, sometimes bordered by a small rim, stepwise located on rapids-waterfall sections of the channel. In the study area, we have found them only in the middle course valley of the Kipyashchaya river (Baransky volcano, Iturup Island). The Kipyashchaya river has a salinity of 4 g/l, sulphate-chloride calcium-sodium composition with content SiO$_2$ of more than 300 mg/l, pH 1.4 [11]. Judging by the results of silicate analysis, the festoons in this section of the channel were formed by a process of the deposition of siliceous sinter (up to 93 %).

The most pronounced example of armored steps of a waterfall was observed in the lower part of the valley of the Kisly brook (Mendeleevo volcano, Kunashir Island). Lighter eversion hollows with a diameter of up to 0.5–0.7 m and a depth of up to half a meter with a rounded pebble and small-boulder material on the bottom and small channel troughs are stand out well against the background of 5 steps of the waterfall covered with a dense brown crust. The results of geochemical analysis showed that the arming of the steps was due to the deposition of siliceous sinter (SiO$_2$ – 79–86 %) with the participation of iron oxides and hydroxides (3–6 %). The thickness of the dense crust varies from 5 to 10 cm. Armoring of the waterfall steps is also observed in the Geyzernaya river basin (waterfalls Igrushka, Troinoy, etc.), and Kipyashchaya river (Iturup Island), but such well-defined steps are rare.

Laminated sinter formations are formed in the valleys near thermal springs and geysers: shields (or aprons), walls and sinter terraces. Shields and walls made of geyserite are most widely represented in the valley of the river Geyzernaya in the area of the Geysernoye thermal field, where chloride sodium springs with a mineralization of 1.8–2.2 g/l dominate. Here, cone-shaped or isometric structures from geyserite, a dense layered siliceous agglomerate, are also formed around long-lived thermal springs and geysers. Their height can reach 1–2 m and more. Large cones are often framed by sinter sub-horizontal or inclined formations – the so-called shields (or aprons), which overlap the adjacent areas in the form of a blanket. They are composed mainly of
geyserite. Geyserite walls are ledges or sub-vertical sections of the valley sides below the outlet of thermal springs, covered with sinter crusts of varying thickness; their area sometimes reaches several tens of square meters. One of the most large-scale formations in river valleys with hydrothermal manifestations can be sinter terraces – terrace-like surfaces formed by deposits of thermal waters at the outlets in the sides of the valley. Good examples are observed on the slopes of the Mendeleev volcano: in the valley of the Kislyi brook at the outlet of the springs of the Lower group and in the valley of the Zmeinyi brook at the Stolbovskie springs. Thermal waters in the middle reaches of the Kislyi brook valley (at an absolute height of about 120–130 m) flow out in the floodplain and in the ledge of a 5-meter terrace, mainly at the left side. Their waters are ultra-acid, nitrogen, chloride-sulfate sodium with pH 1.6–2.1, containing SiO₂ up to 140–250 mg/l with a total salinity of 2.5–4.0 g/l [2, 11, 13]. A sinter terrace with a height of about 1.5 m and a length of up to 10–15 m, composed of silica (33 %), oxides and hydroxides of Fe (23 %) and SO₄ (14 %), has been near the ledge of a 5-meter terrace. The temperature of the Stolbovskie thermal springs, which flow out along the left side of the Zmeinyi brook in its middle reaches, is about 80 °C, the soil above them is warmed up to 40–60 °C. Neutral (pH 6.7–7.0), nitrogen, chloride-sulfate sodium hydrothermal fluids flow out here through small griffins, the walls of which are covered with a snow-white coating of sulfur formed due to the activity of sulfur bacteria [2, 11], which oxidize gaseous sulfur compounds (H₂S and SO₂). At the site of the main water outlet, a small sinter terrace with a height in the central part of about 1.5 m above the brook was formed, upstream and downstream its surface decreases to 0.5 m, its total length is about 7–10 m. This sinter formations consist of silica – up to 42 %, CaO – from 21 % to 52 %, oxides and hydroxides of Fe – up to 7 %, and Al – up to 12 %.

3.2. Specificity of the accumulation of alluvial deposits in the valleys
It should be noted that alluvial deposits in the study area are formed as a result of erosion and processing of hydrothermally altered volcanic and volcanic-sedimentary rocks, both as a bedrock, and displaced and processed by glacial, slope, mudflow processes, as well as chemogenic sediments. Both in the process of moving in the channel of the watercourse, and during deposition and burial, the pebble material is exposed to the aggressive effects of thermal waters and continues to erode, which is clearly seen in the analysis of the boulder component of the alluvium of the Kipyashchaya river draining the slopes of the Baransky volcano (Iturup Island), carried out by [14]. Our analysis of pebble material from watercourses on the Kunashir Island (Lesnaya river, Kislyi brook, Valentiny brook) has also shown that weathered by hydrothermal solutions sometimes altered to saprolite material dominates there: the content of altered pebbles ranges from 43 % to 96 %. The depth of weathering crust of pebbles is on average 2 cm. The fragments of floodplain and terraces covered with layered dense crusts and/or composed of alluvial deposits weathered by hydrothermal processes, and their erosional fragments of various sizes in channels occur in the considered valleys. Moreover, there are two types of alluvium processing by mineralized waters. Strong cementation of alluvial deposits is more often observed, as a rule, with ferruginous and ferromanganese solutions.

3.3. Slope processes and mudflow accumulation in valleys
Hydrothermally altered rocks, weathered to clays, are easily eroded by surface waters, sometimes badlands are formed at these areas, but more often the formation of slips and landslides occurs. Plastic moist clays are an ideal substrate for the formation of numerous displacements on the slopes, as a result of which local multilevel terraces are formed on the sides of the valleys. Due to this fact, the valleys themselves in such areas expand significantly, so they acquire beads-like shape in plan [15–17]. On the slopes of the valley of the Kislyi brook in its upper reaches, for example, we have found out up to 4 levels of such terraces, which are large blocks of displaced hydrothermally altered rocks, which indicates a high activity of landslide processes.
The observations carried out in the valley of the Geyzernaya river also clearly show that its sides are characterized by active development of various gravitational slope processes [17–19], which often form mudflows. In the bottom of the valley, there is an accumulation of slope material displaced as a result of rockfalls and landslides, with periodic blocking of the valley and the formation of temporary dams and dammed lakes, in which the accumulation of river sediments occurs. Further redeposition of the slope and alluvial material occurs during the destruction of dams with the formation of mudflows. We have already considered this process in more detail earlier [17].

4. Conclusions

Hydrothermal zones of areas of active volcanism are geosystems, in the formation of which endogenous energy is actively involved. Within such areas, the physical and chemical properties of rocks change greatly, specific forms of meso- and microrelief are created, and vegetation changes. In geomorphological terms, the watercourse valleys with gas-hydrothermal manifestations differ significantly from valleys without them. First of all, due to the fact that they are exposed to chemical and thermal effects, their waters become warm, highly mineralized, and specific accumulative processes take place in the channels and valleys. The mineralization of waters and the presence of geochemical barriers, where the precipitation of compounds from aqueous solutions takes place, is of great importance for the development of forms of accumulative relief.

As a result of complex interactions with thermal waters in river valleys, the following occurs:

1) the formation of specific accumulative forms of micro- and mesorelief both in the channels and on the sides of the valleys due to the deposition of new mineral formations;
2) processing of alluvial deposits and bedrocks with hydrothermal solutions, which leads to a radical change in their properties and, accordingly, in the characteristics of fluvial processes: there is an intensification of erosion of rocks weathered to clay in some areas, and in others, on the contrary, erosion slows down, rapids are often formed in the case of cementation of sediments;
3) activation of slope processes in areas of gas-hydrothermal manifestations with the formation of rockslide bodies and landslide masses, due to which the accumulation of displaced slope material occurs in the bottoms of the valleys, followed by its redeposition by mudflow processes.

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