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ВЛИЯНИЕ ГАЗОГИДРОТЕРМАЛЬНОЙ ДЕЯТЕЛЬНОСТИ НА ФОРМИРОВАНИЕ РЕЛЬЕФА РЕЧНЫХ ДОЛИН ГЕОТЕРМАЛЬНЫХ ЗОН

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Выходы сольфатарных газов, грязевулканические проявления, минерализованные термальные воды способствуют формированию разнообразных, иногда весьма специфических форм рельефа в днищах и на бортах речных долин территорий современного вулканизма. Проведена типизация денудационных и аккумулятивных форм преимущественно микро- и мезорельефа в речных долинах геотермальных зон в условиях проявлений газогидротермальной активности. Рассмотрены особенности влияния газогидротерм на характер геоморфологических процессов в пределах речных долин, проанализированы причины интенсификации склоновых процессов и эрозии. Основные выявленные закономерности типичны для большинства долин с газогидротермальными проявлениями, что подтверждают наблюдения в долинах рек, дренирующих склоны вулканов Тихоокеанского огненного кольца (в том числе Курильских островов, Камчатки, Новой Зеландии, Северной и Южной Америки), а также Исландии.

Ключевые слова: вулканизм, термальные воды, денудационные формы рельефа, аккумулятивные формы рельефа, склоновые процессы, выветривание, цементация

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1. INTRODUCTION

Thermal waters and gases are formed in areas of increased heat flow. The source of water for hydrothermal springs is mainly atmospheric water but in the process of filtration, its composition largely changes compared to the initial one as a result of interaction with volcanic gases and rocks (Rychagov, 1993). Thermal springs solutions and steam-gas emissions from fumaroles intensively change both the host rocks and the geothermal zones landscapes.

Sites of active gas-hydrothermal manifestations are often found in the river valleys of modern and Late Pleistocene volcanism territories (fig. 1). This is due to the fact that the initiation of river valleys, as well as the location of thermal waters and gases outlets, is usually associated with fault and increased fracturing zones. But the influence of gas-hydrothermal manifestations on the fluvial relief formation is poorly understood: most studies are devoted to the analysis of the geological and hydrogeological structure of geothermal zones, the nature of hydrothermal manifestations, and the features of rock transformation under conditions of gas-hydrothermal impact (Belousov, Sugrobov, 1976; Hedenquist, Browne, 1989; Rychagov, 1993; Chudaev, 2003; Frolova et al., 2011; Bortnikova et al., 2013; Ladygin et al., 2014; Churchill et al., 2021).

The purpose of this research is to fill this gap and to analyze the effect of gas-hydrothermal activity on the nature of relief formation processes in the river valleys, as well as to classify the forms of denudation and accumulative relief the formation of which is directly or indirectly associated with the gas-hydrotherms activity.

2. MATERIALS AND METHODS

The research is based on the route studies carried out in the volcanic regions of North and South America, Iceland and New Zealand, as well as on the analysis of the largest geothermal zones of the world (Yellowstone, El Tatio, Taupo, Iceland, the Valley of Geysers) literary material and the satellite images study from these regions. Detailed geomorphological studies were carried out in the streams valleys on the slopes of Mendeleev and Baransky volcanoes (South Kuril Islands), Mutnovsky and Uzon-Geysernaya caldera (Kamchatka), where the key object was the Geysernaya River valley. The studies of river valleys and fluvial landforms morphology, the nature of the processes on their slopes and at the bottoms of the valleys, the

Fig. 1. River valleys with the different gas-hydrothermal manifestations: (a) – the Covunco River floodplain with geysers Los Tachos, alluvial and debrisflow deposits cemented by thermal solutions are visible nearby (Domuyo vlc., Argentine); (b) – hot waters of the Waimangu Stream upper reaches (Taupo Volcanic Zone, New Zealand); (c) – the sinter wall Vitrazh and (d) – geyser Bol'shoi edifice and sheet – both in the Geysernaya River valley (Uzon-Geysernaya caldera, Kamchatka, Russia); (e) – the boiling pool framed by sinter formations at the Fal'shivaya River right tributary floodplain (Mutnovskyi vlc., Kamchatka), (f) – geyser edifices in the Salado River upper reaches (El Tatio geyser field, Chile). Here and further photos of the author.

Рис. 1. Долины рек с различными газогидротермальными проявлениями: (a) – пойма р. Ковунко с гейзерами Лос-Тахос, рядом видны аллювиальные и селевые отложения, сцементированные термальными растворами (влк. Домуй, Аргентина); (b) – горячие воды в верхнем течении ручья Ваймангу (вулканическая зона Таупо, Новая Зеландия); (c) – натечная стенка Витраж и (d) – гейзеритовая постройка и плащ гейзера Большой – оба в долине р. Гейзерной (Узон-Гейзерная кальдера, Камчатка, Россия); (e) – кипящий котел, обрамленный натечными образованиями в пойме правого притока р. Фальшивая (влк. Мутновский, Камчатка), (f) – гейзерные постройки в верховьях р. Саладо (гейзерное поле Эль-Татио, Чили). Здесь и далее фото автора.

distribution of gas-hydrothermal manifestations areas and denudation and accumulation processes, the weathering features and secondary changes in channel sediments, the composition of neoformations composing accumulative landforms were carried out. The material composition results analysis of these territories' accumulative neoformations were published by us earlier (Lebedeva, Zharkov, 2022), and R.V. Zharkov (2014) also studied the thermal waters composition of the Kuril Islands. Therefore, in this work, we will not touch on these issues in order to focus on the river valleys relief features.

3. RESULTS. TYPIFICATION OF THE LANDFORMS ASSOCIATED WITH THE GAS-HYDROTHERMAL MANIFESTATIONS IN THE RIVER VALLEYS

For the first time, a typification of micro- and mesorelief forms resulting from the direct or indirect gas-hydrothermal activity impact in the geothermal zones' river valleys was carried out. The results are summarized in table 1. The influence of gas hydrotherms on the nature of the relief formation processes within the river valleys is considered. The russian geologists (Belousov, Sugrobov, 1976; Rychagov, 1993; Chudaev, 2003; Bortnikova et al., 2013) distinguish three main types of gas-hydrothermal manifestations: steam-gas emissions, mud volcanic manifestations, and thermal springs. As a rule, all of them are observed in solfatara fields – areas of the most active and high-temperature gas-hydrothermal manifestation. With more distance from the volcanic structures centers and the volcanic activity extinction, there are predominantly thermal springs of various physical and chemical properties, the temperature and mineralization of which also gradually decrease with the distance from the volcanic center.

3.1. Denudation landforms. The denudation processes are confined mainly to the valleys slopes – first of all to their upper part. Here, the *detachment cracks* are often formed. On the Geysernaya River valley slopes their width can reach 1–4 m, and the length – tens of meters. This would seem to be quite natural for the majority of deep valleys, but in our case the relationship between the cracks formation and hydrothermal activity is evidenced by soil vaporization areas within their range (Pinegina et al., 2008; Dvigalo, Melekestsev, 2009). The rocks weathering and moistening processes stimulate a wide range of *slope processes* (rockfalls, landslides, slumps, flow slides etc.) with the *landslides scarps* formation of various lengths and heights. In 2007 on the left side of the Geysernaya River valley, as a result of the hydrothermally altered deposits blocks collapse, a horseshoe-shaped collapse amphitheater was formed (about 150 m high and up to 800 m long, with almost a vertical wall), and in 2014 – a new wall (up to 200 m high and about 480 m long) was formed upstream.

The denudation is also observed on the *soaring sites* – the hot gas outputs areas, under the influence of which there is an active bedrock weathering. Here, the dissolved substance removal and the fine particles washing out during rains and snowmelt, underwashing, and fine-grained material deflation take place. A peculiar phenomenon on the sides of such valleys called *hydrothermal pediments* – which are slightly inclined (1–5°) platforms, the width of which is usually measured by a few meters, but they can reach even a several tens of meters. They are usually formed in the hydrothermal manifestations areas, where weathering is accompanied by increased moistening of the clayey rocks. Their formation occurs due to the gradual slope retreat, destruction material of which is carried out by seeping waters mainly during a planar washout (Lebedeva, 2019).

Unvegetated thermal areas with the pliable weathered rocks are actively eroded, and *badlands* can be formed on the valley slopes. Often the valleys themselves are deep V-shaped incisions. The Yellowstone River Grand Canyon, which depth reaches 270–340 m, and the Geysernaya River valley (depth up to 400–500 m), on the sides of which intensive hydrothermal rocks processing is clearly visible (fig. 2), are the most striking examples of this. *Erosion outliers* of various sizes are often found in the channels of actively downcutting streams, which are both fragments of denser bedrocks – lavas, dikes, extrusions of various compositions, or cemented pebble-boulder deposits. *Rapids and waterfalls* are usually associated with the such formations outlets in the channels.

Denudation niches of several square meters in size are formed on slopes and ledges above many thermal springs and geysers (in the steam and water emissions influence zone). They have different configuration – from a slightly concave ellipsoid to a reminiscent of small caves. In some cases, similar forms are also formed above mud volcano manifestations, but this is rarely observed.

The denudation forms in the valleys bottoms can be divided into the ground and underground. For *soaring sites* and solfataric fields, the subsurface cavities formation of various sizes (up to 0.5–1.0 m^3 and more) is typical due to the rocks dissolution when interacting with the steam saturated with aggressive gases, including sulfurous gases, and the material removal as a result of underwashing and chemical erosion. When the roofs of these cavities collapses, various *linear and isometric hollows* (small depressions) are formed on the surface. On the floodplain and terraces, and sometimes directly in the channels, so-called *pools (basins)* are observed – boiling, mud, which sometimes have a shape of *funnels*. From these small depressions filled with boiling water or mud, an active removal of dissolved and suspended matter occurs, especially intensifying during rains and floods periods (fig. 1, (e)).

Table 1. The landforms associated with the gas-hydrothermal manifestations in the river valleys
Таблица 1. Формы рельефа, обусловленные газогидротермальными проявлениями в долинах рек

Denudation landforms		Geomorphological position of gas-hydrothermal manifestations and their types	Accumulative landforms		
		A. Gas-hydrothermal manifestations in the valleys bottoms			
Soaring (steaming) sites		***1. Steam-gas emissions***	Cone-shaped edifices around solfataras		
Linear and isometric hollows			Native sulfur crystal brushes		
			Evaporation crusts		
Subsurface cavities			Sulfur knolls		
Mud pots		***2. Mud volcanic manifestations***	Mud	tiny volcanoes	
				tongues	
				framing rings	
Erosion outliers		***3. Thermal springs***	Terraces fragments composed of hydrothermally altered alluvial and debrisflow material	cemented	
				weathered to clay	
Rapids and waterfalls			Floodplain fragments composed of pebble-boulder material cemented by thermal waters		
Pools and funnels			Layered formations	In channels	armored steps of waterfalls
					channel troughs
					festoons
				Crusts on the floodplain and terraces surfaces	
		....	Laminated sinter formations	Sinter	terraces
Geyser basins					walls
Underground forms	conduites	***including geysers***		Geysers’	cones-shaped or isometric edifices
	cavities				sheets (shields)
Detachement cracks		**B. Different gas-hydrothermal manifestations on the valleys slopes**	Landslide and block-slide terraces		
Landslides scarps					
Hydrothermal pediments			Landslide and debrisflow dams		
			Debris flow	embankment	
Denudation niches				terraces	
Ravines, deep valleys			Mudflow covers		
Badlands					

The surface denudation forms are also *geysers basins*, which have different sizes (from tens of cm to more than 10 m). Sometimes they have a very bizarre configuration – more often when they are located on slopes, less often – when they are located on a subhorizontal surface – they are almost round. The underground forms, sometimes having a complex structure (Muñoz-Saez et al., 2015), include *tubes or conduits* (depends of their size) and *cavities* of geysers. Often, these tubes depth is measured in the first tens of meters: for example, at the Strokkur geyser (Iceland), it exceeds 20 m with a width of about 2 m (Walter et al., 2020). Thermal springs and mud pots have also their own underground supply *conduits* of a more modest size.

3.2. Accumulative landforms. In the bottoms of the valleys under consideration, as well as at the slopes foot, along with erosion, accumulation dominates in

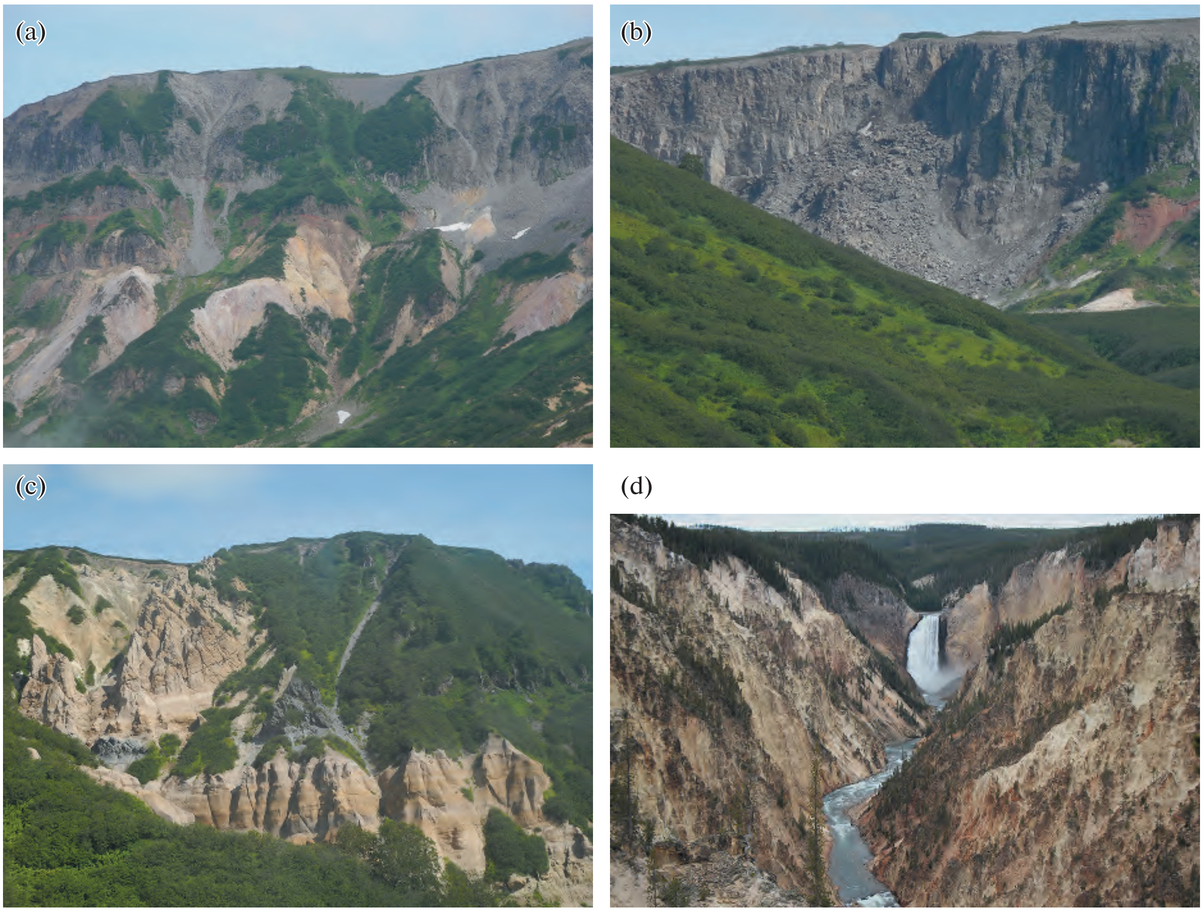

Fig. 2. Processes on river valleys slopes: (a) – landslides, (b) – rockfall, (c) – erosion and block landslides (Geysernaya River valley, Kamchatka, Russia) and (d) – erosion and rocks shedding (Yellowstone River Grand Canyon, Yellowstone, USA).

Рис. 2. Процессы на склонах речных долин: (a) – оползни, (b) – обвалы, (c) – эрозия и блоковые оползни (долина р. Гейзерной, Камчатка, Россия) и (d) – эрозия и осыпи (Большой Каньон р. Йеллоустон, кальдера Йеллоустон, США).

extended areas. Among the accumulative forms associated with the steam-gas vents, *brushes of sublimate crystals*[1] (each up to 1–2 cm height) along cracks in the *soaring sites* and the *solfataras cone-shaped edifices* up to 1–2 m high can be distinguished, also formed from the brushes of crystals, chemical composition of which is determined by the outgoing steam-gas jets composition, where sulfur usually dominates. Often there are *sulfur knolls* a few tens of cm high, also composed mainly of sulfur deposits, but not so well crystallized. The *soaring sites* are often covered with the brittle *evaporation crusts* (1–2 cm thick, sometimes wavy or intricately curved) that are formed on their surface as a result of the vapor–gas mixture interaction with the rocks. Often they mask the *subsurface cavities*. After the watercourse crosses the solfataras field downstream, there are usually observed traces of sulfur floods and sulfur interlayers of various thicknesses in the alluvium.

The mud pots – are the funnels and the small basins (as a rule, up to 3–7 m in diameter) filled with the liquid clay mass, which is a mixture of surface water with the steam and volcanic gases condensates and the clay particles of hydrothermally altered rocks – belong to the denudation forms. However, the accumulative *framing rings of clay material* a few tens of centimeters high are formed around them; sometimes the deposits of clay masses flows – the *mud tongues* – are traced with a length of a few meters, less often tens of meters. In some areas near the pots there are small groups of the *miniature mud volcanoes* tens cm of hight. Often these forms are located on the floodplain, respectively, during floods or during the rainy season, the removal of clay material by water flows can be observed there. In some cases, the mud volcanic forms are confined to the low terraces. For example, in the Geysernaya River valley they are located on a terrace-like sur-

[1] Sublimated crystal brushes and evaporation crusts can rather be attributed to relief nanoforms.

face with elevations of about 30 m above the river's level.

The accumulative landforms created with the thermal springs participation are the most widely represented. Three types of the *layered accumulative formations* are confined directly to the riverbeds: 1) the *channel troughs* – gutter-like channels sections a few meters long and up to 1.0 m wide, 2) the *festoons* – sites up to 0.5–1.0 m in size with a rounded edge stepwise located on the rapids-waterfall channel sections, 3) the *armored steps of waterfalls* covered with a layered crust, sometimes with the *evorsion kettles* with a diameter of up to 0.5 m.

The next group is represented by the *laminated sinter formations* in the bottom of the valley and on the low terraces. These are the *sheets (aprons) or the shields* – horizontal or inclined covers up to 100–400 m^2 in area, framing the c*one-shaped or isometric edifices* of geysers and thermal springs (fig. 1, (d, f)). The dimensions of these structures are measured in the first meters: usually their heights do not exceed 3–8 m, and their diameter can reach 2–5 m or more (Karlstrom et al., 2013). They can have a variety of shapes – from a simple more or less pronounced cone to sometimes very complex structure in the form of the medieval castle ruins (the Castle Geyser, Yellowstone). The *sinter walls* are also distinguished – subvertical ledges of the terraces and sides of valleys below the thermal springs outlet, covered with the sinter crusts of various thicknesses, ranging from a few square meters to tens of meters. One of the most expressive is the Vitrazh wall in the Valley of Geysers (Kamchatka – fig. 1, (c)). The *sinter terraces* of various sizes and morphologies are often encountered, formation of which occurs in the marginal parts of the valleys due to the sinter deposits accumulation. As a rule, their area ranges from the few square meters to the tens, but in some cases – for example, in the Mammoth Springs area in the Gardner River valley (Yellowstone, USA), the size of such terraces reaches hundreds of square meters (fig. 3). The listed formations arise near the springs and the geysers as a result of outpouring or seepage of the mineralized thermal waters. All of them have a layered (or laminated) structure, which indicates the cyclical nature of their formation, which is usually seasonal.

In the valleys under consideration, fragments of the floodplain and the terraces are ubiquitous, covered with the layered crusts of newly formed minerals and/or composed of the alluvial and debrisflow deposits processed by the hydrothermal gas or water, and also their erosional outliers of various sizes in the channels. In this case, the formation of layered crusts is associated not only with the vapor-gas mixtures release but also with the water inflow from the thermal springs on the terraces surfaces. There are two types of the pebble-boulder (alluvial and debrisflow) material processing by the mineralized waters. Strong cementation of deposits, as a rule, by the ferruginous solutions is more often observed. The second type is the sediments weathering to the clays with the alluvium structure preservation. In the channel and on the floodplain, there are frequent different form outcrops of cemented units of pebble-boulder deposits – traces of the past accumulative processes, "fixed" by the thermal impact.

The hydrothermal clays distribution and the presence of the steam and thermal water outlets on the valleys slopes favor the numerous displacements, resulting in the formation of the local multi-level *landslide and block-slide terraces*. In some cases, several tiers of the similar terraces can be observed. In such areas, there is a significant widening of the valleys due to active slopes flattening. At the same time, in the bottoms, there is an accumulation of the slope material, displaced as a result of landslides and collapses with the periodic blocking of the valleys and the formation of the temporary *dams* and the dammed reservoirs, in which the river sediments accumulate. The dams length can reach 500–700 m. The further slope and alluvial material transportation and redeposition occur mainly due to the *debrisflows*, which are formed either directly during the gravity collapses, or during the dams destruction and the descent of temporarily dammed reservoirs. This is well confirmed by the observations carried out in the Geysernaya River valley (Pinegina et al., 2008; Dvigalo, Melekestsev, 2009; Lebedeva et al., 2020), where currently there are 2 similar dams – one (2007) is already cut by the river, and the other (2014) is in the early stages of erosion. The debrisflow deposits form the accumulative *terraces*; in the valleys of some watercourses, the *debrisflow embankments* with a length of a few hundred meters remain, which sometimes undergo cementation. During mudflow material splashes, the recorded heights of which can reach 40 m (Atlas..., 2015), *the mudflow material covers* with a thickness of 0.5–1.0 m to 3–5 m remain on the valley sides and its terraces. Similar debris and mudflow traces are typical of other watercourses of the high hydrothermal activity territories not only in the Kuril-Kamchatka region but also in most volcanic regions of the world (Lebedeva, 2018, 2019).

4. DISCUSSION. THE RELIEF FORMATION UNDER THE CONDITIONS OF GAS-HYDROTHERMAL MANIFESTATIONS

Endogenous energy is actively involved in the geothermal zones formation. Accordingly, in the gas-hydrothermal activity areas, the relief formation occurs under the thermal and the chemical processes impact. Due to the soil warming, the matter transformation occurs there all year round, even in temperate climates. The studies carried out have shown that the gas-hydrothermal manifestations can be confined both to the bottoms of river valleys (more often) and to

Fig. 3. The sinter terraces in the river valleys: *actively developing*: (a) – the Salado River upper reaches (El Tatio geyser field, Chile), (b) – the Sernaya River upper reaches basin (Baranskyi vlc., Iturup Is., Russia); *actively developing* (light) and *to varying degrees overgrown*: (c) – the Gardner River and (d) – the Firehole River valleys; *overgrown*: (e) – the Gibbon River valley; *disintegrating*: (f) – the Gardner River valley near Mammoth Springs (c–f – Yellowstone, USA).

Рис. 3. Натечные террасы в долинах рек: активно формирующиеся: (a) – верховья р. Саладо (гейзерное поле Эль-Татио, Чили), (b) – верховья бассейна р. Серной (влк. Баранского, о-в Итуруп, Россия); с активно формирующимися (светлыми) и в разной степени заросшими участками в долинах: (c) – р. Гарднер и (d) – р. Файрхоул; заросшие: (e) – долина р. Гиббон; разрушающиеся: (f) – долина р. Гарднер у Маммот-Спрингс (c–f – Йеллоустоун, США).

their slopes. The valleys themselves in the gas-hydrothermal activity areas have a peculiar structure with the specific forms of micro- and mesorelief.

Activation of the denudation processes in the geothermal zones river valleys occurs as a result of not only (1) *the flowing waters physical impact*, when the planar washout, linear erosion and the underwashing develop, and (2) the increased *slopes wetting* in the places where water and steam come out – where the landslide dominates, but also (3) the *chemical and thermal effects* of mineralized water and gas-rich steam, leading to the rocks dissolution and weathering. The most dynamically specific exogenous processes develop in the solfatara fields, where the lithogenic base is affected by the highest temperature gases and highly mineralized

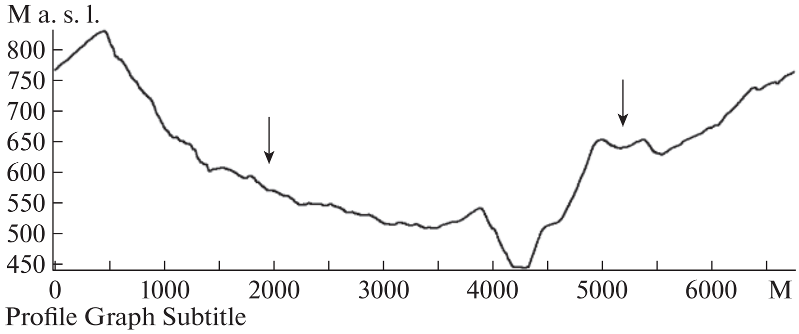

Fig. 4. Cross profile of the Geysernaya River valley (Uzon-Geysernaya caldera, Kamchatka, Russia) in its lower reaches. Arrows indicate areas of different types and ages landslides.

Рис. 4. Поперечный профиль долины р. Гейзерной (Узон-Гейзерная кальдера, Камчатка, Россия) в ее нижнем течении. Стрелками указаны участки оползней разного типа и возраста.

solutions, as well as on the valleys slopes, where the gas-hydrothermal action stimulates gravitational processes and erosion. Such territories are characterized by the successive catastrophic processes chains (Lebedeva, 2018; Lebedeva et al., 2020): the displacement of the slope material of significant volumes – the debrisflow – the formation of a dammed lake – the dam destruction – the repeated debrisflow.

The weathering in the regions under the consideration can proceed in the different ways. During the propylitization, rocks are compacted, their porosity is reduced, and their elastic and strength characteristics are increased. When the loose rocks strata is treated with the thermal solutions, especially those containing iron oxides and hydroxides, their *cementation* often occurs. However, the *rocks transformation into hydrothermal clays* is also widely observed, when their specific cohesion decreases by 1–2 orders of magnitude (Frolova et al., 2011), they acquire the plastic properties, but often retain their original color and structure. Moreover, this applies to both the bedrock volcanogenic rocks and the alluvial and the debrisflow deposits. The researchers (Scaringi, Loche, 2021), in turn, have established an increased clay rocks sensitivity to the temperature changes, which is associated with the physicochemical behavior of their microstructure, due to the presence of the absorbed water and the complex chemical bonds. Thus, as a result of the gas-hydrothermal impact, the composition and the properties of the loose sediments and bedrocks change, and, accordingly, the nature and the rate of relief formation processes. Moist clay substrate is easily eroded, the gravitational processes are activated on the slopes, all this leads to more intense denudation and the river valleys widening (fig. 4). On the contrary, rapids and waterfalls form in the riverbed at the outlets of cemented sediments, and the erosion slows down.

For the accumulative relief formation, the thermal springs waters composition and the geochemical barriers presence are of greatest importance, where the certain chemical compounds precipitate from the solution with the formation of the fluvial relief micro- and mesoforms. At the same time, as a rule, the microrelief forms, measured at a few meters, less often by tens of meters, are directly related to the gases and the thermal waters outlets (as and nanoforms), and the mesoforms, measured by tens – hundreds of meters, are due to the gravitational processes activation in the gas hydrotherms development areas on the slopes and subsequent processes of mudflow formation.

The layered formations in the channels (troughs, festoons, armored crusts) are formed mainly in the areas of rapids, where water is saturated with oxygen and the soluble compounds pass into an insoluble form and precipitate. The new formations in the form of layered crusts in the channel, alluvial deposits cementation can also be observed at the other geochemical barriers: at the watercourses confluences or their flow into water bodies with a different chemical composition of water. It is important to note that accumulative forms similar in morphology both directly in the channel and sinter formations on terraces and slopes can be formed with the different composition thermal waters participation and with the various compounds precipitation. For example, in the Kuril-Kamchatka region – from the siliceous tuffs to the jarosite (Lebedeva, Zharkov, 2022).

The field observations and the interpretation of multi-temporal images show that the gas-hydrothermal manifestations are generally characterized by the spatial migration: in some areas, thermal activity fades, in others it appears over time. In this case, transformation of the associated denudation and accumulative processes and, the forms of relief takes place accordingly. With attenuation of the gas-hydrothermal activity, the relief formation processes rates also fade or change their character, because the rocks temperature and their moisture change. The landslide bodies and the sinter forms gradually overgrow and morphologically look like the ordinary river terraces, which require special attention when studying such areas at the post-volcanic stage (fig. 3, (c–e)).

The rates of the sinter forms formation depend on the activity of the newly formed insoluble compounds precipitation process. In the Kuril-Kamchatka region, these processes have been studied very poorly: a single ^{14}C dating of a dwarf pine branch buried in geyserite indicates that the formation rate of the geyserite cover in the Geysernaya River valley (Troinoy geyser) was about 0.4 mm/year; modern processes observations show a rate of about 0.1 mm/yr (Sugrobov, Sugrobova, 1990; Sugrobov et al., 2009). Also in (Atlas..., 2015) the accumulation rate is estimated as 1–2 mm/year. Accordingly, large sinter structures in the Valley of Geysers are approximately 800–1000 years old. In the Yellowstone caldera, the age of the Castle geyser structure, about 5 m high with the base (shield) with an area of more than 400 m^2, was estimated by pollen (Churchill et al., 2021) as approximately 5500–11 000 years. Measurements taken near the borehole at the Hipaua-Waihi-Tokaanu geothermal field in Taupo Volcanic Zone (New Zealand) showed a silica sinter accumulation rate of about 10 mm/year, at a distance about 35m it decreases to 3.5 mm/year (Campbell et al., 2020). Experiments carried out (Lynn et al., 2019) showed that the silica sinter accumulation rate on small plates in thermal springs of the same Taupo zone varies within 3.9–7.6 mm/yr and depends on their orientation relative to the current, while the maximum accumulation rate observed not inside the water mass, but near its surface – during the water evaporation, and largely depends on its chemical composition.

The strength of new formations in the channels and on the slopes depends on their composition: the deposits saturated with the iron oxides and the hydroxides, as a rule, are more stable in time, and siliceous and carbonate compounds are rather quickly destroyed (fig. 3, (f)). In general, however, the accumulative forms described above for the most part (perhaps with the exception of sediments cemented by iron-manganese compounds) are poorly and rarely preserved after the end of the hydrothermal activity phase. However, the observations (Lynn, 2012) show that in case of repository, the amorphous silica in the form of opal transforms into the stable quartz over time. The findings of hydrothermal paleozones with the fossil geyserite formations are rather few, as well as their dates. In Russia, late Quaternary geyserites were found in Baikal rift zone on Olkhon Isl. (Sklyarov et al., 2004; Velokoslavinskii et al., 2017). Important steps towards the paleoforms study have been made by the specialists from New Zealand and the United States using mass spectrometry (Lynn, 2012; Campbell et al., 2018; Churchill et al., 2020). In some cases, the age of paleogeyserites was determined according to stratigraphy or using argon dating. The most ancient sinter forms fragments within the geothermal fields of these regions are up to 11–16 thousand years old and even 1 Ma (Lynn, 2012).

5. CONCLUSION

We have carried out the typification of the denudation and the accumulative relief forms, formation of which is associated with the gas hydrotherms within the volcanic regions river valleys. The main forms of micro- and mesorelief, directly or indirectly associated with the various gas-hydrothermal manifestations are identified; their characteristics are given, and the morphometric parameters are described.

These results allow us to conclude that in the geothermal zones stream valleys are formed under conditions of the numerous gas hydrotherms outputs of various compositions. As a result of complex interaction with them, the hydrothermal solutions rework the alluvial deposits and the bedrocks. This is why their properties change radically as well as the features of the denudation processes course. In the areas of rocks weathered to clays, their erosion intensifies, the deep erosion incisions and the badlands are formed. In case of sediments cementation, on the contrary, the erosion slows down, rapids and waterfalls are formed.

In such valleys, in the areas of weathered rocks and the gas-hydrothermal manifestations, slope processes activation is observed with the numerous, sometimes multi-tiered landslide terraces formation, which leads to a gradual river valleys widening, which eventually acquire a beads-like shape in plan. Such territories are characterized by a displacement of the significant volumes of material from the slopes, frequent debrisflows, and the dammed reservoirs formation.

Both in channels and on the river valleys slopes, due to the new mineral formations deposition, the specific forms of micro- and mesorelief arise, complicating and transforming the fluvial relief. The various chemical compounds fallout with formation of the characteristic landforms occur mainly on the geochemical barriers (in areas of rapids, waterfalls, in places where springs come out, etc.).

The main revealed patterns are typical for the most valleys with the gas-hydrothermal manifestations both in the Kuril-Kamchatka region and in the world, which is confirmed by observations on the geyser fields of Iceland, New Zealand (Taupo Volcanic Zone), America (including Yellowstone, El Tatio etc.).

GAS-HYDROTHERMAL ACTIVITIES IMPACT ON THE RELIEF FORMATION OF GEOTHERMAL ZONES' RIVER VALLEYS

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Solfataric gases outputs, mud volcanic manifestations and mineralized thermal waters contribute to the formation of various, sometimes very specific landforms on the slopes and the bottoms of river valleys in the modern volcanism territories. It has been carried out the typification of denudation and accumulative forms of predominantly micro- and mesorelief in river valleys of geothermal zones under the conditions of gas-hydrothermal activity manifestations. The features of gas hydrotherms influence on the nature of geomorphological processes within river valleys are considered, and analysed the reasons for intensification of the slope processes and erosion. The main patterns revealed are typical for the most valleys with gas-hydrothermal manifestations, which is confirmed by observations in the river valleys, draining the slopes of volcanoes of the Pacific Ring of Fire (including the Kuril Islands, Kamchatka, New Zealand, North and South America), as well as of Iceland.

Keywords: volcanism, thermal waters, denudation landforms, accumulative landforms, slope processes, weathering, cementation

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