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Impact of the Major Eruption of the Shiveluch Volcano (April 2023, Kamchatka) on Ecosystems: The Extent of Forest Burial and Damage Based on Satellite Data

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Abstract—During the strong eruption of the Shiveluch volcano in April 2023, the active dome collapsed, the pyroclastic flows were released, and large-scale ashfall occurred. Satellite images from the Sentinel-2 satellite have determined the extent of area buried by high-temperature deposits (~60 km²) and assessed the diversity of buried and lost ecosystems. Pyroclastic deposits from the collapse overlaid the southeastern sector of the volcano over an area of more than 50 km² at an altitude of ~2000–500 m above sea level. Below this area, the riverbeds and valleys up to a height of ~150 m were filled with narrow tongues of pyroclastic flows. The deposits of the tongues occupied an area of 12 km²; the lower boundary of one of them is located 22 km from the eruption center. Forest and dwarf alder vegetation was destroyed over an area of approximately 24 km², primarily buried (up to 85% of the area), and also died due to trees being overwhelmed by pyroclastic flow plumes and due to the impact of pyroclastic surges. In the pyroclastic flow impact zone, the destroyed forests are formed primarily of birch *Betula ermanii* and larch *Larix cajanderi*, as well as thickets of dwarf alder *Alnus fruticosa*. An ash layer over 1 cm thick covered an area of over 10 000 km² in central Kamchatka. In the forest belt on the slopes of Shiveluch, ash 6–10 cm in thickness was deposited; woody plants largely survived. Post-eruptive phenomena in the form of secondary ash transport and the redeposition of pyroclastic material washed away by watercourses will continue for many years and will lead to the formation of new zones of damage and vegetation loss.

Keywords: volcanism, eruption, environmental dynamics, forest vegetation, pyroclastic flows, pyroclastic surges, Kamchatka

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INTRODUCTION

A paroxysmal eruption of the Shiveluch volcano (central Kamchatka) occurred on April 10–13, 2023. According to initial eyewitness reports, intense ashfall resulted in an ash layer up to 8 cm thick in the village of Klyuchi (45 km south of the volcano) (Grishin et al., 2024). Eruption was later found to be accompanied by pyroclastic flows, whose deposits covered a vast area. Satellite imagery revealed that the eruption had a particularly large-scale environmental impact, making it the largest volcanic event in Kamchatka in recent decades. The first data on the ashfall parameters and its environmental impact were published (Girina et al., 2023; Grishin et al., 2024). This study, using satellite imagery from the Sentinel-2 satellite, determined the extent of pyroclastic flow deposits and identified the scale of the impact on the natural environment of the region, including the burial and destruction of forests. It also assessed the diversity of destroyed vegetation. In addition to analyzing satellite data, brief field studies conducted in this area in August 2023 and earlier, in 1996 and 2012, were also used (Grishin et al., 2000, 2015).

CURRENT ACTIVITY OF SHIVELUCH VOLCANO

Shiveluch (elevation 3283 m) is the northernmost volcano in Kamchatka, one of the largest and most active. Eruptive products are andesites, which determines the explosive nature of eruptions with large-scale destructive consequences. In recent centuries, particularly powerful eruptions occurred in ~1430, ~1650, 1854, and 1964 (Melekestsev et al., 1991; Ponomareva et al., 2015). As a result of catastrophic eruption in 1964, a volcanic desert (Fig. 1) with an area of approximately 100 km² was formed on the southern slope (Gorshkov and Dubik, 1969; Belousov and Belousova, 1995). A large active dome has been growing in the volcano's crater since 1980. Periodic moderate eruptions (in 1993, 2001, 2004; etc.) were accompanied by collapses of parts of the dome, ash falls, hot avalanches, and pyroclastic flows. Due to the morphological features of the volcano, the main directions of rockfalls, hot avalanches, pyroclastic flows and surges are oriented towards the southern slopes. A significant portion of volcanic rock flows along the valley of the Baydarnaya River in the south-



Fig. 1. Shiveluch volcano massif. Areas covered by deposits from major recent eruptions (numbers correspond to the year of eruption). (1) Stary Shiveluch summit (elevation 3283 m); (2) active dome. Image from Sentinel-2 satellite, July 1, 2023.

western sector of the volcano, as well as that of the Kabeku River in the southeastern sector. Large eruptions with pyroclastic flows (Fig. 1) occurred in 2005 and 2010 (Zharinov and Demyanchuk, 2013). Pyroclastic flows are a mixture of hot ($>500^{\circ}\text{C}$) debris and gas; flows move at high speed down the volcano's slopes, burying riverbeds and valleys with their sediment. The flows are accompanied by pyroclastic surges—gas-saturated turbulent eddies containing sandy material. Surge speeds are tens of meters per second, and temperatures are several hundred degrees Celsius.

VEGETATION STATE BEFORE THE 2023 ERUPTION

Vegetation of the region is distributed over deposits of varying genesis and age. The area affected by the 2023 eruption is characterized by two main natural complexes. The first complex was located above 500 m above sea level and until April 2023 was a volcanic desert with extremely sparse vegetation (Grishin et al., 2000). This part of the affected zone is formed by deposits from the 1964 eruption and deposits from the 2010 eruption located to the east (Figs. 1, 2a). The former were landslide deposits, cold from the eruption's moment; the latter were landslide/pyroclastic hot deposits (locally hot; judging by the thawing of the snow cover, they remained until April 2023). The second complex was located below 500 m; here, forest vegetation, along with some meadow and dwarf alder

vegetation, prevailed on old (approximately 600 years old) deposits of previous volcanic catastrophes. In the altitudinal range of 200–460 m above sea level, the forest vegetation of stone birch *Betula ermanii* and larch *Larix cajanderi* is located on hilly deposits of a giant landslide that occurred during a catastrophic eruption in the late Pleistocene (Ponomareva et al., 2015). Thickets of dwarf alder *Alnus fruticosa* dominate the upper parts of hillsides. Below 300 m, larch forests predominate, often with the participation of stone birch and other deciduous tree species (Fig. 2a). A spruce (*Picea jezoensis*) forest massif is located on the southwestern foothills of Shiveluch, while in the southeastern sector of the volcano, spruce forests are found only in places and, as a rule, sparsely.

SCALE OF VOLCANIC MATERIAL DEPOSITS

During the eruption, in addition to intense ashfall, the active dome collapsed. Materials that made up the dome collapsed in a hot avalanche south of the dome, then passed through and were deposited on the southeastern slope (Fig. 1, 2b). The vertical range of eruption products from the dome to the lowest point of the deposition was approximately 2000 m, and the maximum extent was approximately 22 km. Three zones can be conditionally distinguished (Fig. 2b), which we will call the zones of transit (zone I), accumulation (zone II), and long-distance passage of pyroclastic flows (zone III).

The transition zone extends 7–8 km south of the active dome. Its upper half extends to an altitude of ~ 1300 m above sea level along a lifeless slope overlain by volcanic deposits from previous eruptions, deposited repeatedly over recent decades. Between 1300 and 800 m above sea level, the zone turns south-southeast, and sections of fresh deposits appear on the slope in patches, stripes, and ridges. Toward the lower boundary of zone I, these patches become more numerous, joining in places to cover up to 70–80% of the territory. The area of visible 2023 deposits in zone I, according to the image from April 29, 2023, is approximately 10.5 km^2 .

The accumulation zone is a field of $\sim 38\text{ km}^2$, completely covered by hot deposits. The deposits lie on the southeastern slope, in an altitude range from 800 to 400–500 m above sea level. The field extends from top to bottom for almost 8 km, widening in a bell shape, and has a width at the bottom of ~ 7 km. In the lower part of zone II, deposits completely blocked the Kabeku River valleys and three of its tributaries, with the third tributary having a nearly V-shaped incision more than 50 m deep (Grishin et al., 2015). The 2023 deposits overlaid deposits from the previous eruption (October 2010), which in the thickest strata remained hot until the 2023 eruption, judging by snow thawing over an area of $\sim 2\text{ km}^2$.

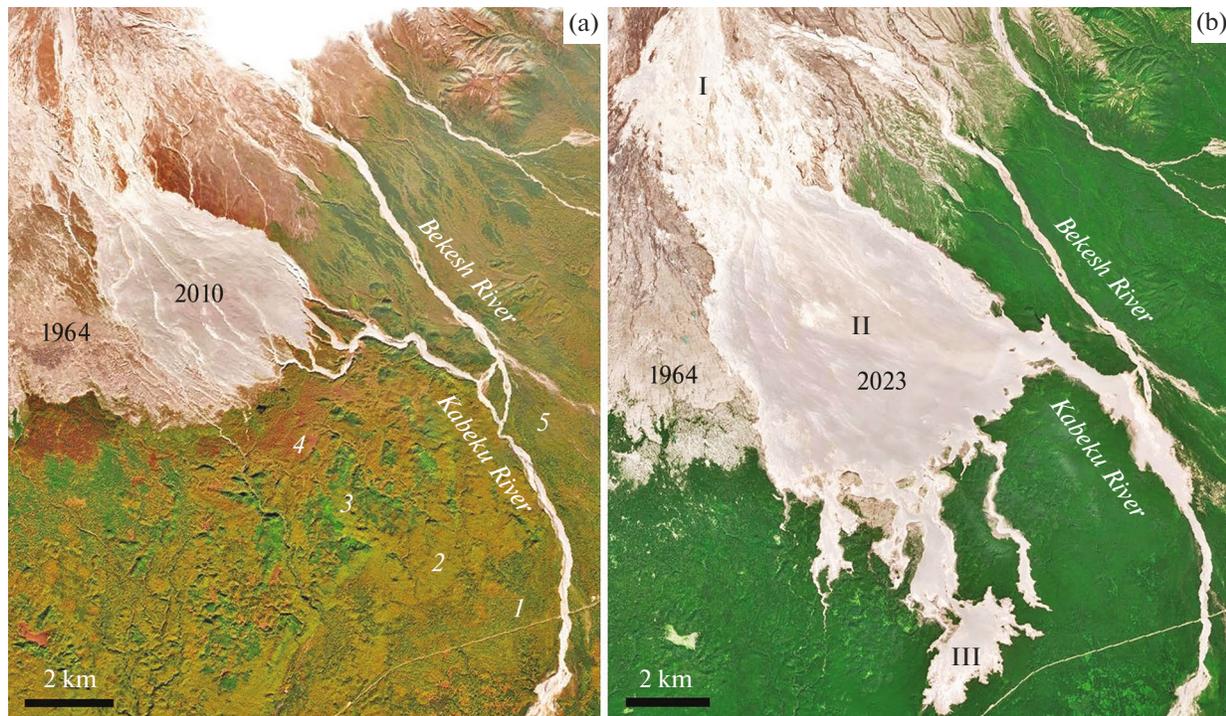


Fig. 2. Southeastern slope of Shiveluch: (a) the state before the 2023 eruption. The numbers indicate the predominant vegetation: (1) larch forests; (2) birch forests; (3) dwarf alder thickets; (4) a complex of meadows, dwarf alder thickets, and forests; and (5) mixed valley forests and dwarf alder thickets. The year of eruption is indicated in the areas overlain by volcanic deposits. Image from Sentinel-2 satellite dated September 24, 2022; (b) deposits from the 2023 eruption, deposit zones: (I) transit zone, (II) zone of large-scale accumulation of pyroclastic deposits, and (III) zone of long-distance passage of pyroclastic flows. Image from Sentinel-2 satellite dated July 1, 2023.

Below zone II, the pyroclastic flows descended along riverbeds and valleys, resulting in five distinct flow branches that formed zone III (Fig. 2b). The eastern branch traveled 4.5 km along the Kabeku River valley, descending to 220 m above sea level. The width of its high-temperature deposits reached 1 km. The central branch, the largest in area, descended along an old, forested riverbed to 145 m above sea level, traveling approximately 6 km. At its terminal end, its plume spread in a large fan through the forest (mainly larch), covering an area approximately 3 km wide and only 400–500 m short of reaching the regional highway (Figs. 2b, 4b). The total area of deposits from all pyroclastic flow branches was ~ 12.5 km².

TEMPERATURE AND THICKNESS OF DEPOSITS

Temperature of pyroclastic flow material during deposition exceeds 500°C. In thick (tens of meters) strata, the temperatures can remain very high for several years or even decades, while at the surface they decrease rapidly, especially during the cold season. Field measurements in August 2023 in zones II and III showed that sediment temperatures at a depth of 50 cm reached 50–65°C. In many places where the topography allowed thick sediment strata to form, the steaming

fumaroles with steam outlet temperatures of 200–300°C were observed. It was found that series and chains of fumaroles were associated with buried riverbeds.

In zone I, by the spring of 2024, the snow covering most of the deposits had ceased to melt. This meant that the deposits had cooled and, consequently, they were relatively thin. Only a small portion of deposits, represented by a chain of islands in the zone's axial part, remained snow-free, meaning they remained hot.

Over most of zones II and III, the deposits remained hot during the first year after the eruption, judging by the snow cover melting in the spring of 2024. Severe frosts in the winter of 2023/2024 led to the cooling of most of the surface; under these conditions, snow thawed only in areas of deep incisions in V-shaped valleys, where the thickness of deposits reached 50 m (Fig. 3a). When frosts weakened in the spring of 2024, the snow thaw resumed over most of zone II (Fig. 3a). Thus, the multi-meter-thick deposits overlaying the gentle slopes in zone II did not cool during the long, frosty (for mountain conditions) winter. However, due to the different thickness of deposits, the intensity of thaw varied. Large areas covered by unmelted snow indicate the presence of thin deposits within the contour of zone II. Their total area is approximately 8–12 km², and the deposit thickness is

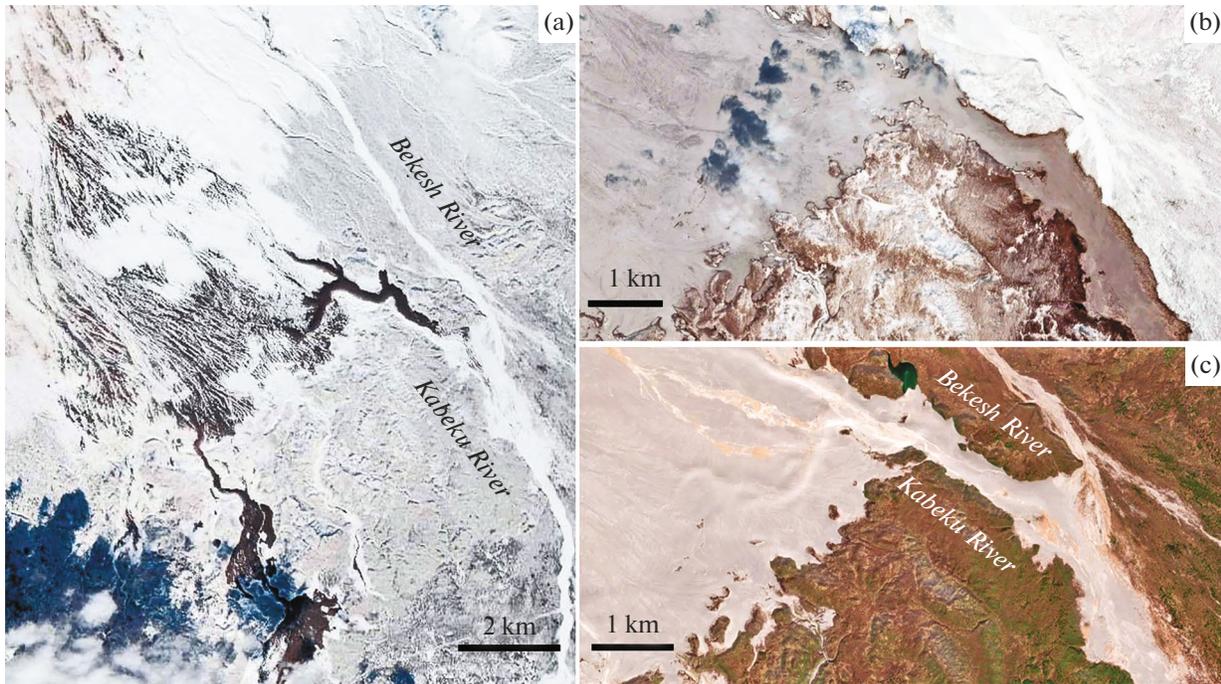


Fig. 3. Transformation of the surface of pyroclastic deposits: (a) thawing of snow cover on hot pyroclastic deposits of 2023 eruption. Sentinel-2 image from March 24, 2024; (b) zone II southeastern part, the valleys of Kabeku River and its tributaries are buried. Sentinel-2 image from April 29, 2023; (c) the same area 13 months later: sediments in the buried tributary valleys have subsided; fresh sediments have marked new channels; a dammed lake has formed (top, middle). Sentinel-2 image from June 5, 2024.

estimated to be 1–5 m. Satellite images from March 2024 show that the majority of zone II remains warm. The structure of the passage and deposition of material is clearly visible: subparallel bands of hotter deposits (bare substrate) alternate with bands of cooled surface covered by snow.

In zone III, snow initially thawed on the surface of deposits of most of the largest flows (“central” flow and the Kabeku River valley). Thawing on the remaining pyroclastic flows was absent or fragmentary, meaning their deposits were thin.

Thus, based on the snow cover thawing, it is possible to judge the temperature and, accordingly, the thickness of deposits, and also to conditionally identify zones of different thicknesses: presumably 30–50, 10–25, and up to 5 m. As a result, it is possible to preliminarily estimate the total volume of pyroclastic deposits in zones I–III at 0.4–0.5 km³.

The change in topography caused the local damming of one of the streams, which had been blocked by pyroclastic deposits. This resulted in the formation of a lake, which by early summer 2024 had reached a length of 700 m and an area of approximately 0.08 km² (Fig. 3c).

BURIAL OF FOREST AND DWARF VEGETATION

Erupted pyroclastic deposits pushed downward the boundary between the volcanic desert and the forest

(Fig. 2). This boundary shifted by ~1–2.2 km, decreasing vertically from 490–540 to 400–500 m above sea level. The new boundary between the volcanic desert and the lower slopes with surviving forest turned out to be sharp; there are more than a dozen forest islands ~50–500 m in diameter above and close to the boundary (Figs. 2b, 4a). These represent the upper parts of hills, whose bases were buried by deposits of moving pyroclastic flows. Between the former and new boundaries, a contour formed, ~7 km long along the front and with a total area of ~11 km², where forest, meadow, and dwarf alder vegetation were completely buried. In addition to the closed vegetation of forest belt, the 2023 pyroclastic deposits buried the extremely sparse vegetation cover on the 1964 deposits (west of zone II) and the meadow–dwarf alder vegetation (east of zone II).

Below zone II, the forest vegetation was buried by deposits from five pyroclastic flow tongues. The thickness of sediments reached several tens of meters in the deeply incised channels of the largest tongues (at an altitude of 390–450 m above sea level). For the most part, forests of stone birch and larch, as well as thickets of dwarf trees, primarily alder, were buried. As a rule, along the buried channels, along the axial part of tongues, continuous deposits were noted, without dead trees or fallen broken trunks. These deposit strips contain a thick layer of pyroclastic material, which remained hot even a year after the eruption. In the

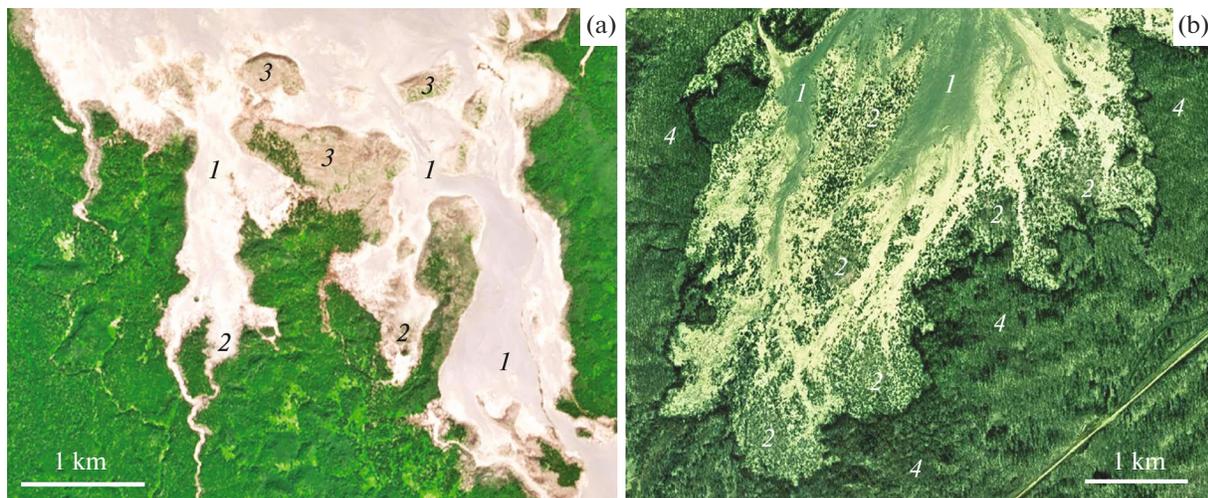


Fig. 4. Death and burial of tree stands: (a) image from Sentinel-2 satellite dated July 1, 2023; (b) image from GeoEye-1 satellite dated April 29, 2023. (1) Zones of thick pyroclastic flow deposits that completely buried forests; (2) areas of destroyed and semiburied forest; (3) areas of forest death under the influence of pyroclastic surges; and (4) forest before the beginning of the growing season, with snow cover under the tree stand canopy.

lower half of tongues, the thick layers of sediments are surrounded by a fringe of semiburied forest (Fig. 4b). The thickness of sediments in this fringe apparently reaches tens of meters; as it moves away from the thick strata toward the living forest, on a distance of 200–400 m it gradually declines. The stand is sparse, the undergrowth is buried, and tree trunks are partially buried, while most are broken or burned at the bases, buried in the hot sediments, and lie on the surface. Sediments in these peripheral zones were hot 4 months after the eruption, and the semiburied wood was smoldering in places. Dead trees were also encountered locally; due to the moderate dynamic impact on the bases of their trunks, they remained standing. The total area of semiburied and dead tree stands in this manner is approximately 2.5 km².

DAMAGE TO FOREST VEGETATION

In the terminal parts (plumes) of pyroclastic flows, which spread across the forest in wide fans, the deposit thickness decreased to 1 m or less; therefore, they cooled quickly. Trees were not blown down and buried, but remained standing. Deposits charred the bases of trunks at the points of contact and also thermally affected the crowns (even scorching; some trees were even burned). As a result, most of the trees died, creating strips and patches of dead stands.

Furthermore, the pyroclastic surges that accompanied the pyroclastic flows left their mark in the form of strips of dead trees along the valley walls in the mountainous terrain. High-temperature gas–sand vortices scorched and partially destroyed the tree stand, causing its death in strips up to ~50–100 m wide adjacent to the flow deposition zones (similar to what happened in the Baydarnaya River valley in 2005 and in

the Kabeku River valley in 2010 (Grishin, 2009; Grishin et al., 2015)).

Forest stands killed by pyroclastic surges and thin pyroclastic flow plumes are located primarily over 200 m above sea level; they consist predominantly of Erman's birch. Meanwhile, larch forests located below 200–220 m were destroyed (trees broken, charred, and felled) or died (without significant external damage) due to partial burial by thicker pyroclastic flow deposits.

The beginning of the growing season (image from June 26, 2023) revealed the scale of tree stand loss from the passage of thin pyroclastic flow plumes and pyroclastic surges—approximately 3.5 km². The largest area of dead tree stand, ~0.8 km², is located in the western part of contact zone II sediments and the forest (Figs. 2b, 4a). Mountain forests of Erman's birch there died over an area up to 1500 m wide and up to 700 m deep. In forest islands located near the lower boundary of zone II, the trees and dwarf alder thickets were also largely lost. In a number of islands, it is clear that in their northern (upper) half, the tree vegetation was completely destroyed by the impact of pyroclastic surges, while in the southern half, it partially survived, protected by the terrain.

Overall, forest and dwarf alder vegetation, including coniferous forests, was buried and destroyed over an area of approximately 24 km². According to preliminary estimates, the destroyed forests consisted of approximately 50% Erman's birch, 25% larch (including spruce), approximately 15% mixed and deciduous forests, and approximately 10% alder thickets.

ASHFALL

Ashfall covered a wide sector of the southwestern foothills, as well as areas extending westward (to the

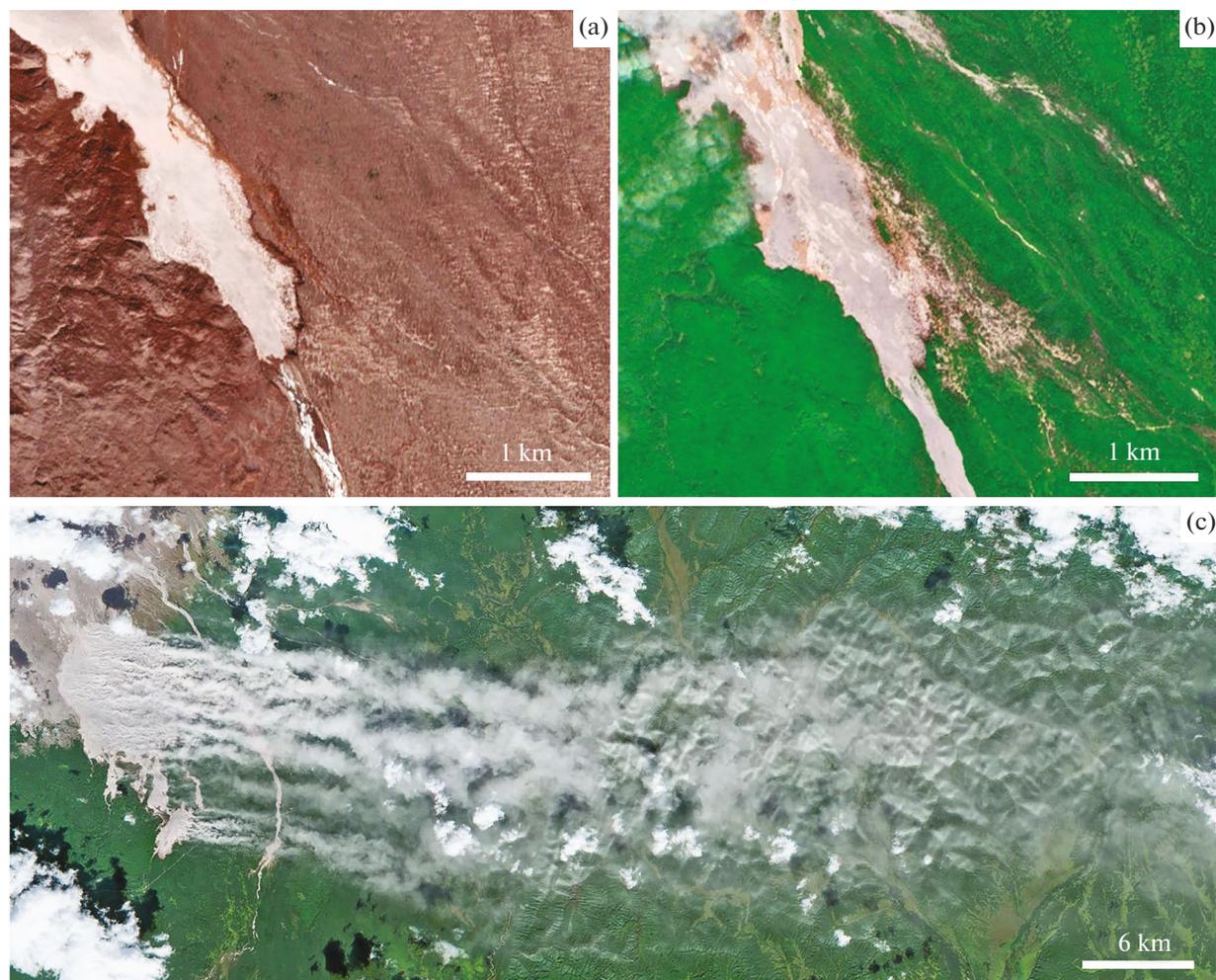


Fig. 5. Post-eruptive phenomena: (a) tongue of the pyroclastic flow in the Kabeku River valley before its erosion. Sentinel-2 satellite image from May 17, 2023; (b) erosion of the area along the Kabeku River left bank by redeposited pyroclastic deposits. Sentinel-2 satellite image from June 17, 2024; (c) transport of ash and fine pyroclastic deposits by strong wind from the deposit field surface of the 2023 eruption (on the left). Sentinel-2 satellite image from September 4, 2023.

Sredinny Range, a distance of approximately 90–100 km), southwest (Kamchatka River valley, approximately 130 km), and south/southwest (northern half of the Klyuchevskaya group of volcanoes). A study of satellite images revealed that, after the onset of the 2023 growing season, the light-colored, dried ash was visible only in areas of exposed soil. In total, more than ten types of natural and anthropogenic landscapes were identified where ash accumulations were detected in satellite images. Using these markers, it was possible to delineate the distribution of ashfall deposits thicker than 1 cm, covering an area of approximately 10 000 km² (Grishin et al., 2024). Assuming, in accordance with our field measurements, an average compacted sediment layer thickness of 2.5 cm, we obtain an ash volume in this area of approximately 0.25 km³. This is a large value even without taking into account the dispersed tephra (which was deposited in a layer less than 1 cm thick). Ashfall of April 11, 2023,

in terms of erupted product, was the largest in nearly 60 years and the largest in Russia in the last 40 years. The negative impact of moderate ashfall on the forest belt vegetation (the thickness of fresh sediments was 6–10 cm) was minimized by a number of factors (thin ash, lack of foliage, and snow cover on which the ash layer fell).

POSTERUPTIVE PHENOMENA

During the snowless period of 2023, the fresh volcanic deposits began to erode and be transported by watercourses. The beginning of this process was recorded in a WorldView-3 satellite image from May 20, 2023: the Bekesh River, which flows into the Kabeku River, erodes pyroclastic flow deposits. This was followed by the erosion of sediments in the Kabeku River upper reaches and its tributaries, the valleys of which were buried by the 2023 sediments. New channels

began to form on the surface of the fresh and hot sediments; in the Sentinel-2 image from June 5, 2024, the six channels are visible, crossing zone II from top to bottom and extending below, into zone III (some of them are visible in Fig. 3c). Pyroclastic deposits carried along these riverbeds are redeposited downstream and engulf forest areas, leading to the drying and death of tree stands. Thus, a large engulfed forest area has begun to form along the left bank of the Kabeku River; by June 17, 2024, its area was approximately 2 km² (Figs. 5a, 5b).

In the vast open spaces above the new tree-line, freshly deposited loose materials will be subject to erosion, and their surface will generate dust in windy conditions. This process was active during the snowless period of 2023, especially when the wind became strong (over 20 m/s, according to the meteorological station in the village of Klyuchi). As a result, thousands of tons of airborne dust were transported not only within the volcanic desert, but also tens of kilometers away from the volcano, reaching the Pacific Ocean (Fig. 5c). These processes were exacerbated by the significant volume of tephra that fell during the massive ashfall of April 11, 2023, and could continue for many years.

DISCUSSION

The 2023 eruption largely repeated the October 2010 eruptive event, when the dome collapsed and the hot masses fell on the southeastern slope; pyroclastic flows descended below a vast accumulation zone; and ashfall occurred in the southern sectors and in the outlying surrounding areas (tens of kilometers from the eruption center). However, the scale of 2023 eruption was significantly larger, with a noticeably larger area of hot deposits. Moreover, the high-temperature deposits of 2023 overlaid the still-warm, hot deposits of 2010, which were present in thick strata.

The 2023 pyroclastic flows traveled significantly further and lower—up to 22 km from the dome (in 2010, up to 18 km); this is the maximum distance for modern eruptions in Kamchatka and the Kuril Islands. Significantly, no lahars (volcanic mudflows) formed, despite the eruption occurring during a period of peak snow accumulation. This can be explained by the exceptional thickness and temperature of pyroclastic deposits, whose rapidly moving flows overlaid the snow cover and instantly evaporated it within their multi-meter-thick, hot mass.

Area of buried forest and dwarf alder vegetation as a result of the 2023 eruption significantly (by an order of magnitude, according to our data) exceeded the area of forest buried during the 2010 eruption. Initially (in April–June 2023), the extent of forest damage from the low-power pyroclastic flow plumes and pyroclastic surges that passed through the forest and dwarf alder trees, causing their death, was unclear. With the

onset of 2023 growing season, we were able to identify affected zones and estimate their area (approximately 3.5 km²) from strips of dead forest.

Overall, the 2023 eruption significantly expanded the area of a vast (over 150 km²) volcanic badland located on the southern, southwestern, and southeastern slopes of Shiveluch. The negative impact of the enormous volume of sediments on the surrounding areas will continue for years and decades to come.

CONCLUSIONS

The powerful eruption in the affected area radically altered the natural environment, with the extensive burial and destruction of ecosystems. High-temperature sediments from the April 2023 eruption formed a multi-meter thick cover blanketing approximately 60 km² of the slopes, significantly lowering the tree-line in its southeastern sector. Pyroclastic flows traveled a record-breaking distance for modern Kamchatka eruptions—up to 22 km from the eruptive center. The impact on ecosystems in the volcano's southeastern sector constituted a localized environmental disaster. Forest and dwarf alder vegetation, including coniferous forests, were buried and destroyed over an area of approximately 24 km².

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CONFLICT OF INTEREST

The author of this work declares that he has no conflicts of interest.

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