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FORMATION OF WATER RUNOFF IN A LAHAR DURING THE 1945 PAROXYSMAL ERUPTION OF KLYUCHEVSKOY VOLCANO

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A high-magnitude lahar was caused by ice and snow melting during the paroxysmal eruption of Klyuchevskoy volcano on January 1 of 1945. The distribution of erupted masses within the glacier-covered zone, where the lahar water phase originated, has been mapped using our own field observations, with reference to published and archive data. Review of factors and mechanisms responsible for volcano-glacier interactions and related lahar hazard, for Klyuchevskoy and other ice-clad volcanoes in the world, made basis for a phenomenological model. The model explains the formation of extremely voluminous water flows in lahars during paroxysmal eruptions for the case of Klyuchevskoy volcano. According to our rough estimates, the meltwater runoff from the lahar initiation zone during the event of 1945 reached 59 million m^3, and the total volume of the lahar could vary from 237 to 355 million cubic meters.

Lahar, debris flow, slush flow, nival-glacial zone, paroxysmal eruption, tephra, pyroclastic flow, lava flow, thermodynamic processes, phreatomagmatic explosion, Klyuchevskoy volcano, Kamchatka

INTRODUCTION

The formation of lahars during eruptions of ice-clad volcanoes is one of most hazardous consequences of volcanism. All volcanoes in Kamchatka and in the Kuriles have a stable snow cover and twenty one of them bear glaciers; most of ice lies on the Klyuchevskoy group volcanoes. Valleys of perennial and ephemeral streams are actual or potential paths of lahars that may travel 30 to 80 km. Especially large lahars flow down the Kirgurich, Krutenkaya, Sukhaya, and Studenaya rivers that originate from the glaciers of Erman and Bogdanovich (Fig. 1) [*Chernomorets and Seynova, 2010; Belousov et al., 2011; Muraviev and Klimenko, 2014; Muraviev and Muraviev, 2016*].

The region of Kamchatka and the Kurile Islands, with their high volcanic activity and abundance of ice and snow, is among most advantageous places where to investigate nival and glacial lahars.

Volcanoes of the Klyuchevskoy group are studied at the Kamchatka volcanological station founded at Klyuchi Village in 1935 [*Fedotov and Masurenkov, 1991*]. The lahar events associated with eruptions of Klyuchevskoy volcano for the past 80 years of its history were described in many publications [*Piip, 1956*; *Vinogradov and Muraviev, 1989; Dvigalo and Melekestsev, 2000; Belousov et al., 2006; Fedotov and Zharinov, 2007; Zharinov and Demyanchuk, 2009, 2015; Seynova et al., 2010; Muraviev and Klimenko, 2014*].

The lahar flow during the paroxysmal eruption of January 1, 1945 was the largest event of this kind in the 20th century [*Piip, 1956; Muravyev and Salamatin, 1994; Dvigalo and Melekestsev, 2000*]. It had no fatal consequences for people only because the flowing mass failed to reach Klyuchi Village. The lahar event lasted one or two days, at air temperatures of –32 °C on January 1 and –25 °C on January 2. The

Fig. 1. Lahar on Erman Glacier during lava flow along Krestovsky trough of Klyuchevskoy volcano (photograph by Yu.V. Demyanchuk, 16.02.2005).

eruption caused ice melting at the northwestern foot of the volcano [*Piip, 1956*].

In this study we reconstruct the lahar formation as a result of snow and ice melting in the climactic phase of the Klyuchevskoy eruption on January 1, 1945. The results for the Klyuchevskoy lahar are compared with data on catastrophic lahars at other ice-clad volcanoes worldwide summarized in our recent publication [*Seynova et al., 2017*].

The flow of meltwater released by interaction between eruption products and ice (snow) controls the volume and destructive potential of lahars (volcanic debris flows). The physics of this phenomenon has no solid theoretical grounds yet [*Thouret et al., 2007*]. The approach in practical studies of causes and consequences in the formation mechanism of catastrophic lahars includes (i) reconstructing past events using available field observations, published evidence, historic and modern maps, and remote sensing data, and (ii) real-time monitoring of volcanic activity [*Major and Newhall, 1989; Huggel et al., 2007; Muraviev and Klimenko, 2014*].

In order to reconstruct the formation of meltwater flow within the nival-glacial lahar generation zone in the case of the Klyuchevskoy eruption of January 1, 1945, we characterize its climactic phase [*Piip, 1956*], assess the role of different volcanic factors in lahar triggering, and constrain the spatial limits of their impact on ice and snow.

We suggest a phenomenological model for the formation of the 1945 Klyuchevskoy lahar by analogy with other models of volcano-glacier interactions that trigger lahars [*Pierson et al., 1990; Thouret et al., 2007*]. Note that the description of local processes is of special theoretical and practical value at different stages of modeling for further justification of appropriate mathematical approximations and calculations [*Vinogradov and Vinogradova, 2010*].

The lahar area of the 1945 event was studied in the field during three trips from June 25 to 30, 2008; August 06 to 13, 2011; and August 12 to 16, 2013, and witnessed the onset of a summit eruption in the last trip (15–16.08.2013). In addition to the field observations, we used scanned aerial images of Klyuchevskoy volcano and Erdman glacier captured in 1949 (a part of volcano slope and margins of the Erman, Vlodavets, and Sopochnyi glaciers) and in 1967 (a part of the Erman glacier margin); satellite images (KH-9 Hexagon of 28.06.1975, Resurs DK-1 of 02.06.2007, SPOT 6 of 22.08.2012, and Kanopus-B 1 of 17.09.2014 and 22.02.2016); a 1:30 000 topographic map of 1935 for a part of the Erdman glacier margin and a General Staff 1:100 000 map (sheets O-57-141, O-57-142, N-57-9, N-57-60) based on surveys of 1976 and 1979. Referencing was made using a SPOT 6 orthophotograph of 22.08.2012. All images were brought to a single system of coordinates (WGS 84, universal Mercator projection, zone 57N). The data were processed in ArcGIS 10.

VOLCANIC AND GLACIAL PREREQUISITES FOR LAHAR FORMATION AT KLYUCHEVSKOY VOLCANO

The conditions and mechanisms of lahar formation depend, respectively, on volcanic activity which controls volcano-glacier interactions, and on the parameters of volcanic edifices and their nival-glacial systems.

Volcanic activity

Klyuchevskoy is a stratovolcano, the highest active volcano of Eurasia (4750 m asl on average) and one of most active ones within the Pacific “ring of fire”. It is a steep almost ideally symmetrical cone composed of pyroclasts and lava cemented with ice [*Fedotov and Masurenkov, 1991*].

The style of volcanic activity and related lahar formation is consistent with its basaltic and basaltic-andesitic magma composition. Most of eruptions are of Strombolian type, with explosions and outpouring of pulverized magma and lava flows upon glaciers. Interaction of lava with ice leads to phreatomagmatic explosions and generation of lahars [*Ozerov et al., 1997; Fedotov and Zharinov, 2007*]. Paroxysmal eruptions include brief phases of subplinian relaxation and pyroclastic flow [*Piip, 1956; Belousov et al., 2011*]. Rapid flow and redeposition of pyroclastic material on ice and snow during Plinian eruptions trigger catastrophic lahar events worldwide.

This is the first study that addresses the contribution of pyroclastic flows to the generation of water flow and related lahar during the climactic phase of the 1945 Klyuchevskoy eruption.

By the time being, evidence is available for eighteen large summit eruptions that yielded about 100 million cubic meters of material, including ten paroxysmal eruptions between 1697 and 2016. Destructive erosion processes were observed in 1737(?), 1829, and 1945 [*Zharinov and Demyanchuk, 2009, 2015*].

The activity of Klyuchevskoy volcano never declined or stopped. It erupts within 10 million m^3 in moderate events every five years on average, while large events (up to 100 million m^3) recur at ~30 years. In the 21st century, moderate summit eruptions occurred in 2003–2005, 2007–2009, 2012, 2013, 2016, and 2017, and only the 2003 explosive event caused no lahar. The activity remains almost invariable, judging by high frequency of eruptions and relative stability of their volume [*Melekestsev, 2006*]. Catastrophic events like that of 1945 repeat at 68 to 96 years [*Muravyev and Salamatin, 1994*].

Effect of volcanism on the glacial system

The glacial system of Klyuchevskoy volcano, controlled by its eruptions [*Vinogradov and Muraviev, 1989*], consists of an ice belt around the cone and a train of passive ice with tongues of active glaciers at its foot (Fig. 2, *a*, *b*). The upper cone part, devoid of

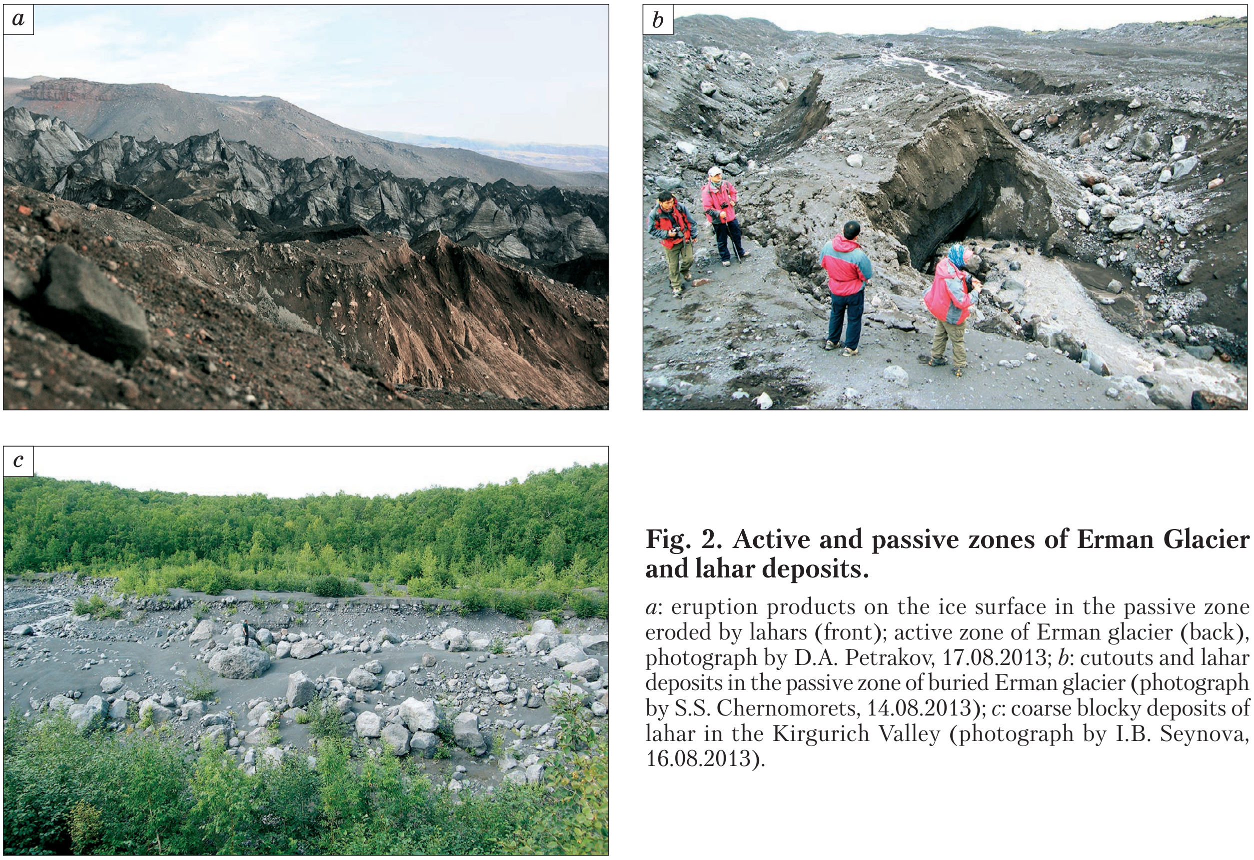

Fig. 2. Active and passive zones of Erman Glacier and lahar deposits.

a: eruption products on the ice surface in the passive zone eroded by lahars (front); active zone of Erman glacier (back), photograph by D.A. Petrakov, 17.08.2013; *b*: cutouts and lahar deposits in the passive zone of buried Erman glacier (photograph by S.S. Chernomorets, 14.08.2013); *c*: coarse blocky deposits of lahar in the Kirgurich Valley (photograph by I.B. Seynova, 16.08.2013).

ice, is composed of periclinal beds dipping at 40°, with alternating unconsolidated pyroclasts, firn, and ice lenses. The 50–60 m thick ice layer covers the volcano slope between altitudes of 4000–3500 and 2700–2000 m asl. The glacier tongues descending to the edifice foot are surrounded by 20–30 m thick bodies of ground ice.

Volcanism affects the mobility of glaciers (Erman, 1945), their advance (Sopochnyi, 1953 and Vlodavts, 1967–1968) and degradation (Kell, 1980). The Erman glacier became 3.3 km longer after the event of 1945 (from 18.2 in 1949 to 21.5 km in 2016) and currently occupies 30.3 km^2 (40.6 km^2 with passive ice) [*Dokukin et al., 2017*].

Pyroclastic fallout on ice makes up tens of percent relative to the glacier volume. Low-density porous pyroclastic material (ash, lapilli, scoria, scoria bombs, etc.) is friable and transforms into voluminous fine-grained slurry masses of lahars [*Kraevaya and Kuralenko, 1985*]. Thus, the glacial system of Klyuchevskoy volcano stores almost inexhaustible resources of both liquid and solid lahar components.

FACTORS OF WATER FLOW FORMATION IN THE LAHAR EVENT OF 1945

As reported by *Piip* [*1956*], "a tremendous stream of meltwater raced about 35 km down the Kirgurich River in the evening of January 1, 1945 and discharged into the Kamchatka River 10 km east of Klyuchi Village. The roar of the stream ... was heard in Klyuchi soon after the end of the paroxysmal eruption ..., within at least 15 km far. Water kept flowing all the day long on January 2, in spite of the frost (–25°). ... On January 6, on our way through the Kirgurich sands, we saw only thick ice belts. The main meltwater stream ... that carried moderate amounts of ash and sand was likely followed by typical mudflows soon after its decay. The mudflow tongues spread out into the forest at the margin of the flat volcano foot and had stopped 2–3 km before the Klyuchi–Kamaki winter road. Five months after the eruption..., the mudflow deposits consisted of moist and swampy black ash-sand masses. ... Upstream, they piled up in thicker stacks, became coarser and, judging by their directions..., were just small offshoots of the main stream that rushed down the Kirgurich" (see the photograph in Fig. 2, *c*).

We have identified active volcanic factors responsible for the formation of the extremely large water flow using our own field data and deciphered aerial images of 1949, with reference to the witness of Piip who observed the eruption and its consequences for the nival-glacial system. The lahar paths during the 1945 eruption of Klyuchevskoy volcano are sketched in Fig. 3.

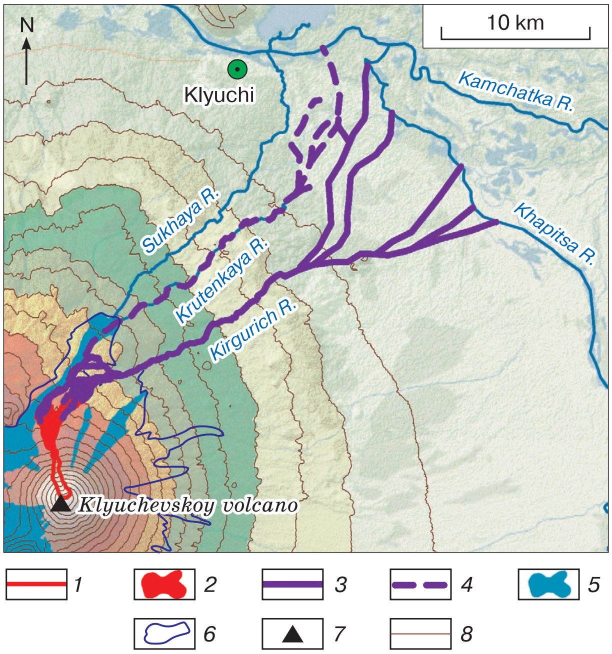

Fig. 3. Sketch map of lahar paths in the Klyuchevskoy eruption of 1945.

1 – Krestovsky trough; *2* – deposits of lava and pyroclastic flows in the glacial zone of Klyuchevskoy volcano; *3* – observed lahar paths [*Piip, 1956*]; *4* – inferred lahar paths; *5* – glaciers; *6* – glacial/periglacial boundary; *7* – main crater; *8* – elevation contour lines (at every 200 m).

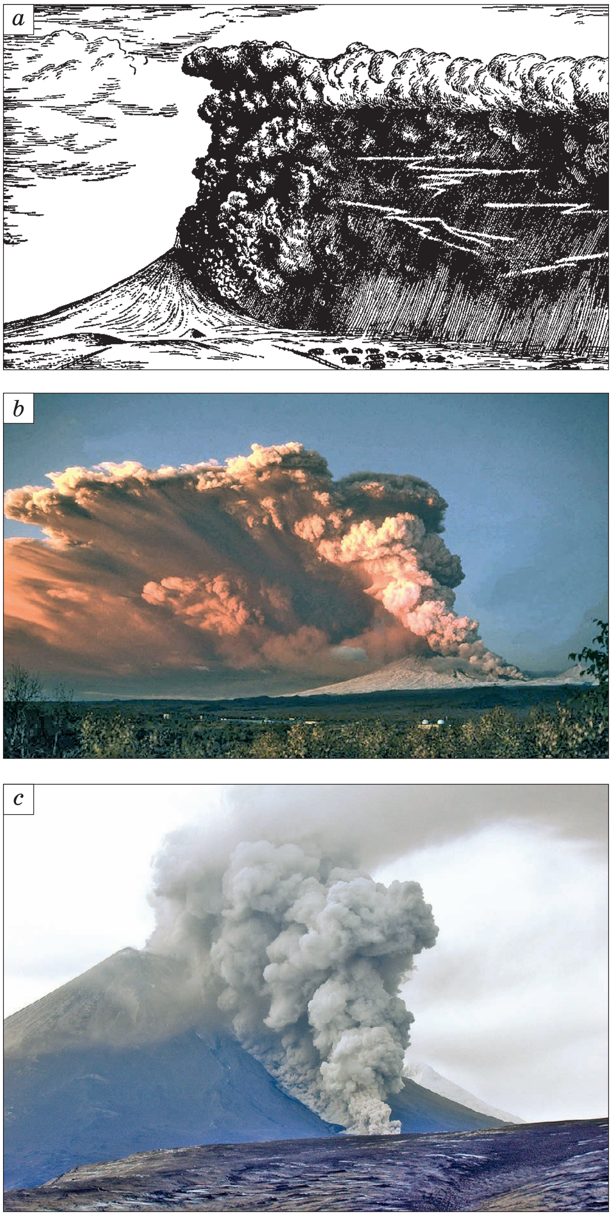

Fig. 4. Pyroclastic flows in Erman Glacier during eruptions of Klyuchevskoy volcano.

a: event of 1945 (picture by *Piip* [*1956*]); *b*: event of 1994 (photograph by A.B. Belousova, 01.10.1994 (http://www.belousov.pro/kluch951.jpg)); *c*: event of 2005 (photograph by A. Lobashevsky, 09.03.2005).

Volcano-glacier interactions during the climactic eruption phase

The climactic phase of the 1945 eruption caused catastrophic changes to the Klyuchevskoy edifice and its glacial system, unprecedented in the 21st century. "A chasm appeared in the northwestern slope of the volcano, descending about 4 km till the gently dipping part of the cone at about 2700 m asl opposite Middle Hill. ... The wide opening of the collapsed crater crest exposed a dome-like hill erupting incandescent lava. ... An immense field of thick hot avalanches spread from the chasm mouth to 2000 m of altitude" [*Piip, 1956*].

The report of *Piip* [*1956*] who observed the climactic phase of the eruption (4:40 a.m. to 8 p.m. on 01.01.1945) from Klyuchi Village reads: "A giant explosive column, tilted northwestward at 20–25 degrees, rose over the crater; its top pierced the huge oblique plume of gases rising as high as 7–10 km. ... A dark veil of ashfall extended to the northwest from the base of the eruptive column". Growing gas-steam clouds, which resulted from sublimation when 0.06 km^3 of hot tephra precipitated on snow, wrapped the volcano cone up to 3000 m asl [*Ozerov et al., 1997*]. Melting of snow and firn under the effect of hot steam and volcanic gases mixed with ash and lapilli produced the first lahar surge. The surge water then froze up into ice layers found 10 km far from Klyuchi Village.

At 5:30 a.m., a gas/ash-laden cloud arose off the main crater when the erupted masses intruded the ice tongue that filled the Krestovsky trough and induced phreatomagmatic explosions [*Dvigalo and Melekestsev, 2000*]. The explosive activity had increased since 11:30 a.m., and the related seismic shocks became felt in Klyuchi Village [*Piip, 1956*]. That was apparently the onset of lava-ice interaction, which lasted till the end of the climactic phase at 08:00 p.m. Secondary phreatomagmatic explosions were much more frequent and destructive than the summit ones [*Ozerov et al., 1997; Belousov et al., 2011*]. The high-energy directed explosion impact broke the moraine-laden glaciers and favored their melting which fed the lahar surge with ever greater amounts of released water.

The effect of volcano-glacier interactions on the lahar formation patterns shows up in different ways depending on the type of volcanic activity that controls the physical properties of the eruption products. The role of pyroclastic flows in meltwater discharge requires additional justification. Strombolian-type eruptions of basaltic lava are common to Klyuchevskoy volcano, but the explosion, with a column tilted at 25° to the horizon [*Piip, 1956*], and the related partial collapse of the edifice slopes (Krestovsky trough) which caused "hot avalanches" rather correspond to a subplinian eruption with pyroclastic flows. In this respect, the term "hot avalanches" used by *Piip* [*1956*] may refer to the formation of pyroclastic flows. Such flows were also observed at Klyuchevskoy during another paroxysmal eruption of 1994, as well as in ordinary events of 1925, 1987, 2005, and 2007 (Fig. 4) [*Belousov et al., 2011*].

Pyroclastic and lava flows

We reconstructed the consequences of the great lahar that arose during the climactic phase of the Klyuchevskoy eruption in 1945, with reference to the evidence of *Piip* [*1956*], by geomorphological analysis of aerial and satellite imagery. The results were used to map the effects caused by the catastrophic event (Fig. 5).

The deposited products of the eruption were detected in deciphered aerial photographs shot in 1949 downslope of the Krestovsky trough mouth at 2700–1900 m asl in the northwestern segment of Klyuchevskoy volcano. Their limits were constrained according to contrasts with distinct static flows of cooled lava, moraines, and active glacier tongues. We traced changes in the morphology and medium-scale relief of the deposits from 1975 through 2016 and compared them with the present position. For this period of time, the glacier has displaced some of the overlying unconsolidated clastic deposits of January 1, 1945, specifically, Piip's "hot avalanches" in the right lobe (contour *6* in Fig. 5). In the first few days after the eruption, the deposited avalanches (pyroclastic flows) remained hot and saturated with gas, judging by steam columns that rose 600–800 m above the surface of the buried glacier, which were followed by gradually waning steam outbursts for about 75 days more [*Piip, 1956*].

The left lobe, which is a pyroclast-laden solidified lava mass occupying the place of molten ice, re-

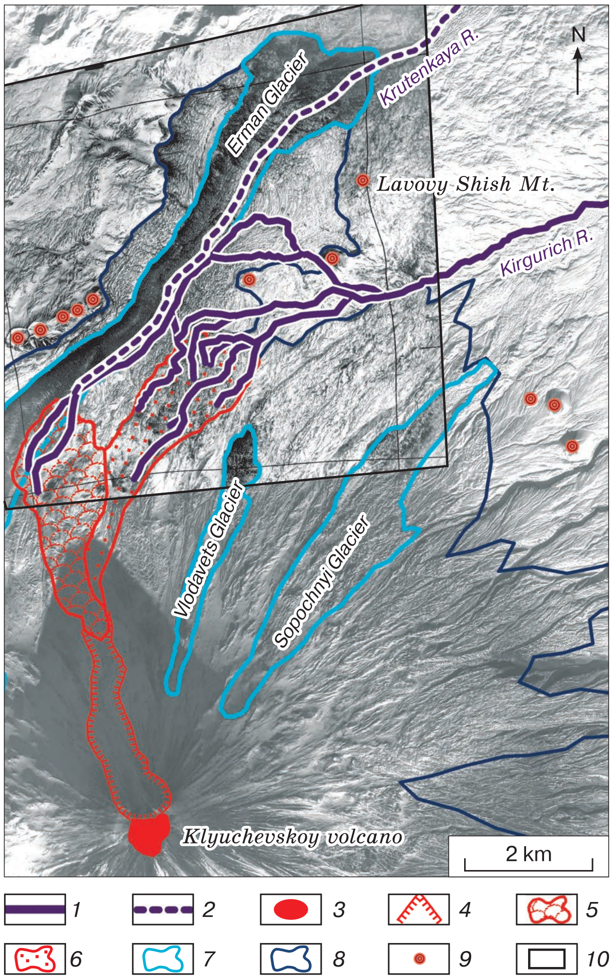

Fig. 5. Consequences of the 1945 Klyuchevskoy eruption.

1 – lahar paths of 1945 described by *Piip* [*1956*] and easily detectable in photographs; *2* – inferred lahar paths of 1945; *3* – main crater; *4* – Krestovsky trough; *5* – lava flow of 1945 (with pyroclastics); *6* – pyroclastic deposits of 1945; *7* – glaciers; *8* – glacial/periglacial zone; *9* – craters of flank eruptions; *10* – limits of aerial photograph captured in 1949. The map is based on satellite image IRS P5 (11.10.2007) and on a transformed aerial photograph of 1949 for the fragment of Erman Glacier and lahar generation zone.

mained almost invariable for the long time (see contour *5* in Fig. 5): all positive and negative meso-scale landforms on its surface are intact. The lobe margin looks upthrown onto the Erman glacier in an aerial photograph of 1949. Piip found high ice scarps on the lobe periphery in the August of 1945 and attributed them to the effect of hot lava flows that melted ice on their way during violent explosive activity for six hours on January 1. Secondary phreatomagmatic explosions commonly result from lava-ice (snow) interaction during Strombolian basaltic eruptions of ice-clad volcanoes. The explosions are triggered by gravity instability at increasing pore and hydrostatic pressures in the lava front. As a result, lava fails and produces large volumes of a gas-pyroclastic mixture; the heavy portion of this mixture creeps downslope as pyroclastic flows [*Belousov et al., 2011*]. The phreatomagmatic explosions associated with the Klyuchevskoy eruptions were considered as precursors to lahars [*Vinogradov, 1985; Ozerov et al., 1997; Dvigalo and Melekestsev, 2000; Belousov et al., 2006; Zharinov and Demyanchuk, 2015*].

Thus, we have revealed the factors that may lead to generation of an extremely large lahar: style and duration of volcanic activity and the area of the volcano-glacier contact. However, the formation mechanisms of meltwater flow during the paroxysmal eruption of 1945 remain controversial [*Muravyev and Salamatin, 1994; Dvigalo and Melekestsev, 2000; Melekestsev, 2006; Belousov et al., 2011*], as the parameters are poorly constrained and the physics of volcano-glacier interaction is still poorly grounded. One possible approach is to proceed from analogy with catastrophic lahars on other ice-clad volcanoes worldwide: Redoubt (Alaska), Saint Helens (Washington, USA), Cotopaxi (Ecuador), Nevado del Ruiz (Colombia), etc. [*Seynova et al., 2017*].

Synthesis of published data [*Major and Newhall, 1989; Waitt, 1989; Pierson et al., 1990; Manville et al., 2000; Thouret et al., 2007; Pistolesi et al., 2014*] and our reconstructions of the climactic phase of the Klyuchevskoy eruption reveal several factors responsible for the formation of water flow in catastrophic lahars, which are common to all ice-clad volcanoes worldwide.

1. Effect of tephra and pyroclastic surge on snow during paroxysmal eruptions that destroy the edifices of stratovolcanoes: Cotopaxi (1877); Shiveluch (1854); Klyuchevskoy (1945); Bezymyanny (1956); Saint Helens (1980), Ruapehu (1995).

2. Effect of pyroclastic flows on the ice-snow cover during Plinian-type eruptions: Cotopaxi (1877); Klyuchevskoy (1945, 1994); Saint Helens (1980); Nevado-del-Ruiz (1985); Redoubt (1990).

3. Effect of lava flows on glaciers during Strombolian-type eruptions: Klyuchevskoy (1945, 1984, and other years); Llaima (1945); Villarica (1948, 1984).

These interactions control the rate and volume of melting on ice-clad volcanoes and trigger the formation of water flow and ensuing gravity flows [*Piip, 1956; Pierson et al., 1990; Thouret et al., 2007; Muraviev and Klimenko, 2014*]. The three types of interactions jointly released tremendous volumes of water during the event of 1945. See Table 1 for contributions of each mechanism.

The formation of water flow during the volcano-glacier interactions is described in the suggested phenomenological model.

FORMATION OF WATER FLOW IN A LAHAR: A PHENOMENOLOGICAL MODEL

Effect of hot tephra on snow

Voluminous fallout of heavy hot tephra on the snow cover of glaciers at Klyuchevskoy volcano, accompanied by extremely rapid growth of steam-gas clouds, led to rapid melting of ice and snow and produced the first water surges of the lahar [*Piip, 1956*]. Similar cases were reported for catastrophic lahars during the explosions of Bezymyanny, Cotopaxi, and Saint Helens volcanoes [*Gorshkov, 1957; Waitt, 1989; Pistolesi et al., 2014*].

Field and experimental studies show that heating by low-density eruption products leads to sublimation and softening of snow to a depth of 2 m. The release of steam into snow maintains *thermodynamic convection* and moistens snow to slush. Subsequent injection of the slush into dense firn causes its displacement, avalanching, and slush flow. Voluminous slush flows can sweep off all snow from the glacier surface and produce great lahars or floods in winter. The total volume of slush and avalanches shed into rivers from snow-covered slopes and glaciers during the explosion of Saint Helens in 1980 reached 100 million m^3 [*Manville et al., 2000*]. The greatest lahar in Kamchatka ($500 \cdot 10^6$ m^3) along the Sukhaya Khapitsa valley was fed with snow from neighbor volcanoes, which melted under the impact of directed-blast sand from Bezymyanny volcano in 1956 [*Gorshkov, 1957*].

Snow melting during fallout of hot tephra upon snow over an area of ~15 km^2 in the Kirgurich River catchment caused the first lahar surges. On average 2 to 8 m of snow accumulates on Klyuchevskoy volcano and in river valleys for a winter season, which corresponds to a water equivalent of 1000–2000 mm [*Muraviev and Klimenko, 2014*]. Melting of 1 m of snow and firn in perennial snowpacks (400 kg/m^3 of total density) under hot tephra in the Kirgurich catchment [*Vinogradov and Muraviev, 1985*] can release up to 6 million m^3 of water.

Effect of pyroclastic flows on ice

A mixture of pyroclastic flows down the Krestovsky trough mantled the glaciers in the northwestern volcano segment from 5:30 to 11:30 on January 1, 1945 (Fig. 3), and the main zone of gravity flow generation moved to the head of the Kirgurich River.

The formation of meltwater flow in catastrophic lahars is largely controlled by *turbulent* motion of incandescent pyroclastics that exert high-energy erosion and abrasion impacts on the surface of glaciers. In some cases, the erosion cutout in the glaciers of Cotopaxi, Redoubt, and Klyuchevskoy volcanoes reaches 50 m in depth and 100 m in width. Case studies of Cotopaxi and Nevado del Ruiz were used to verify the amount of ice loss estimated from physical and numerical experiments. According to experimental data, turbulent flow can maintain ice melting at 0.3–0.9 mm/s while the rate of passive melting is 0.015–0.03 mm/s. These estimates are consistent with field data on the vertical losses of snow and ice: 2.3 to 8.2 m in different segments of Nevado del Ruiz and 4 to 8 m in Cotopaxi [*Thouret et al., 2007; Pistolesi et al., 2014*]. Thermal and wind erosion associated with the advance of pyroclastic flows over the glacier surface can generate tens of million m^3 of meltwater in tens of minutes. As it was shown by measurements along the lahar paths in the ordinary eruption of Nevado del Ruiz of 1985, melting of ice over an area of 4.7 km^2 for 20–90 min produced $22 \cdot 10^6$ to $43 \cdot 10^6$ m^3 of water. In the case of the Cotopaxi catastrophic eruption of 1877, the respective water volume reached $110 \cdot 10^6$ m^3 at the ice area 13.9 km^2 [*Waitt, 1989; Pierson et al., 1990; Thouret et al., 2007*].

The maximum amount of meltwater can be estimated assuming that the mechanism of pyroclasts-ice interaction during the climactic phase of the 1945 Klyuchevskoy eruption was the same as in the cases of Nevado del Ruiz and Cotopaxi. At a reasonable melting rate of 0.9 mm/s, turbulent pyroclastic flows could release about $8 \cdot 10^6$ m^3 of meltwater having removed about 20 m of ice from the 4 km long and 100 m wide Krestovsky trough for six hours [*Dvigalo and Melekestsev, 2000*].

As the pyroclastic flows spread out radially over the glaciers of the flattened volcano foot, the erosion turned to abrasion. The vertical ice loss by abrasion in six hours, from an area of 4 km^2 can be estimated as 6–7 m, assuming a melting rate of 0.3 mm/s. The maximum volume of meltwater could reach $23.4 \cdot 10^6$ m^3, as calculated assuming an average loss of 6.5 m and an ice density of 900 kg/m^3.

The processes of erosion and abrasion by pyroclastic flows were followed by static ice melting under pyroclasts. Static melting is a common effect of erupted material on ice. Heat transfer from hot deposits to the underlying ice can generate 33–56 mm of meltwater in 30 min at a melting rate of 0.015–0.03 mm/s [*Major and Newhall, 1989; Thouret et al., 2007*]. Static melting of a 4 km^2 glacier at 112 mm/h from 11:30 a.m. to 08:00 p.m. on January 1 may have produced $3.8 \cdot 10^6$ m^3 of meltwater.

Effect of lava flows on ice

Interactions of lava flows with ice and snow that lasted from 11:30 a.m. to 08:00 p.m. on January 1, 1945 induced irreversible processes in the glacial zone of Klyuchevskoy volcano: melting of glaciers and burial of moraines [*Piip, 1956*], as well as displacement of the large Erman glacier and melting on its margin.

Outpouring of lava on the glacier surface produced lava lakes and fields with pressure ridges which were growing rapidly, and their growth was accompanied by strong phreatomagmatic explosions preceding the lahar event. Steam and gas clouds rose to a height of 10 km, while the released heat reached $3 \cdot 10^8$ kW [*Belousov et al., 2011; Zharinov and Demyanchuk, 2015*]. The explosions caused glacier failure, whereby the area of ice-lava contact increased and ice melting accelerated. As reported by *Vinogradov* [*1985*], 15–20 m thick lava pillows were rapidly sinking into the melting ice as a result of phreatic explosions. Percolation of hot gas and meltwater along fractures facilitated incorporation of lava into the glacier. Thus, *ice melting and formation of water flow may occur also inside glaciers, at the lava-ice contact, which triggers a chain reaction of failure and increases water release at the account of the within-glacier component*. The lava-ice interaction has been an essential lahar generation mechanism at the present activity stage of Klyuchevskoy volcano. Phreatomagmatic explosions during lava flow along the Krestovsky trough onto glaciers at the foot of the volcano are accompanied by turbulent pyroclastic flows which interfere with static melting and thus increase the melting rate [*Belousov et al., 2011*]. According to observations by *Vinogradov* [*1985*] for a lava field over the Bogdanovich glacier, the lava melted 50–100 m thick ice in 17 days, from 12–13 September to the month

Table 1. **Mechanisms of volcano-glacier interactions: contributions to lahar formation in 1945**

Melting mechanism	Ice (snow) area, km^2	Calculated vertical ice (snow) loss, m water equivalent	Calculated volume, 10^6 m^3
Snow melting by hot tephra	15.0	0.4	6
Ice melting by pyroclastic material, Krestovsky trough	0.4	20.0	8
Ice melting at the volcano foot by wind erosion and pyroclastic flows	4.0	5.85	23.4
Static ice melting under pyroclastics	4.0	0.952	3.8
Ice melting by lava flows	3.0	6.0	18
Total meltwater release			**59**
Increase in the lahar volume in the zone of buried ice and river valleys	4- to 6-fold		
Total lahar size			**237–355**

Note: the total amounts are approximate to million cubic meters, given the low accuracy of specific estimates.

end in 1974, or 3 to 6 m per day. The amount of meltwater released by lava-ice interaction during the catastrophic climactic phase of the 1945 eruption can be estimated at $18 \cdot 10^6$ m^3, given that the ice area was 3 km^2, neglecting slow melting of glaciers after the brief lahar event and assuming an average ice thickness of 6 m by analogy with the Bogdanovich glacier.

Altogether, all agents of the volcano-glacier interactions in the event of January 1, 1945 could jointly release around 59 million m^3 of meltwater (Table 1). This hot saline water cut out narrow scours in glaciers and mixed up with loose material and water in the zone of buried ice and river valleys. Estimates for eruptions of other volcanoes indicate that the lahar volume can become 4–6 times greater below the generation zone [*Huggel et al., 2007*]. The 4–6-fold increase of the estimated meltwater volume gives a lahar size of $237 \cdot 10^6$ to $355 \cdot 10^6$ m^3. The accuracy to a million of cubic meters with the above assumptions is not very rigorous. Anyway, the total lahar volume apparently reached hundreds of million cubic meters, i.e., it was one of the world largest lahars.

CONCLUSIONS

Ice and snow melting during the paroxysmal eruption of Klyuchevskoy volcano on January 1 of 1945 induced the generation of a great lahar. The eruption products in the lahar generation zone were mapped with reference to publications, data archives, and our own field observations. We summarized the factors and mechanisms that drive volcano-glacier interactions and can trigger catastrophic lahars in ice-clad volcanoes worldwide. The obtained data made basis for a phenomenological model to explain the release of water feeding catastrophic lahars during paroxysmal eruptions of Klyuchevskoy volcano. The calculations showed that the contribution of pyroclastic flows to the formation of meltwater flow during the main paroxysmal event was previously underestimated.

According to our estimates, the amount of meltwater in the zone of lahar generation reached $59 \cdot 10^6$ m^3, while the total lahar volume during the event of 1945 could be from $237 \cdot 10^6$ to $355 \cdot 10^6$ m^3.

This approach may be used in studies of large lahars at Klyuchevskoy volcano, as well as in other ice-clad volcanoes of the world. The suggested approach allows estimating the lahar parameters using data collected after the event, which is advantageous because direct measurements of lahars during eruptions are hardly feasible. This estimation should be made with regard to different factors and mechanisms relevant to specific lahars depending on the eruption type and the structure of the glacial-nival systems of volcanoes.

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