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FORMATION OF WATER FLOW IN LAHARS FROM ACTIVE GLACIER-CLAD VOLCANOES

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Glaciers and snow cover on volcanoes are among main sources of meltwater in lahars. Review of open databases on volcanoes, modern glaciers and snow cover allowed us to identify 144 glacier-clad volcanoes as well as 226 volcanoes with and 298 volcanoes without seasonal snow cover. We have compiled a sketch map which illustrates the global distribution of volcanoes covered with ice and snow and analyzed available reports on lahars from such volcanoes. Evidence on eruptions of Redoubt (Alaska, 1989–1990) and Nevado del Ruiz (Colombia, 1985) volcanoes made basis for a plausible model explaining the transformation of volcanic (eruption) to hydrological (lahar) processes. Interaction of pyroclastic flow with snow and ice which causes their melting occurs by the mechanisms of convective mixing and rapid turbulent heat exchange, respectively. The melting rate at turbulent heat transfer is at least ten times faster than that of static melting under eruption products.

Lahar, slush flow, nival-glacial zone, paroxysmal eruption, tephra, pyroclastic flow, lava flow, thermodynamic processes, phreatic blast, volcano

INTRODUCTION

Lahars that form during eruptions of active glacier-clad volcanoes create most serious and far-reaching hazard. Lahars induced by the eruption of Nevado del Ruiz volcano (Colombia) in 1985 that killed 23,000 people in Armero and Chichchiná towns were the most catastrophic in the 20th century [*Lowe et al., 1986; Pierson et al., 1990*]. Note that the magnitude of eruption itself was not very large but its tragic consequences were caused uniquely by the lahars, with their liquid component formed from molten snow and ice (slush flow).

Lahar hazard often arises at volcanoes covered with glaciers or snow, which is a key prerequisite for lahar initiation in Kamchatka and elsewhere. However, the mechanism of eruption-to-lahar transition remains poorly understood, even though lahars occur quite frequently at glacier-clad volcanoes.

The aim of this study was to analyze the mechanism of meltwater flow generation upon interaction of hot pyroclastic material with ice and snow. The work included review and synthesis of data from individual ice- and snow-capped volcanoes, compiling a database and a map illustrating the distribution of present volcanoes with stable ice and snow cover, and revealing lahar formation patterns during the eruptions of Redoubt (Alaska, USA) and Nevado del Ruiz (Colombia) of 1989–1990 and 1985, respectively.

VOLCANIC FACTORS OF LAHAR FORMATION

Volcanic activity monitoring can reveal lahar sources and triggers in the nival-glacial zone. The effect of high-temperature eruption products on ice and snow has been discussed in a number of publications [*Walder, 1992, 2000; Huggel et al., 2007; Thouret et al., 2007*]. In order to understand the underexplored details of water flow generation in lahars, we synthesized published evidence on:

(i) known historic lahar events during eruptions in the Pacific "ring of fire", Iceland, Italy, and Africa, and review of lahar formation conditions at 40 volcanoes worldwide [*Crandell, 1971; Major and Newhall, 1989*]; (ii) classification of lahar causes in the eruption of dacitic-andesitic Nevado del Ruiz volcano that had fatal consequences, as well as in other disasters [*Pierson et al., 1990*].

The formation of lahars during subglacial eruptions of volcanoes fully covered with ice are left beyond this consideration. This phenomenon, known from Iceland where it has the local name *jökulhlaup*, was studied previously [*Björnsson, 1991, 2003; Tómasson, 1996; Russell et al., 2006*], and is worth being a subject of a separate publication. This study focuses on lahars at volcanoes only partially covered with ice.

Water flow in lahars of the nival-glacial zone results from progressive changes in pyroclastic density currents upon interaction with ice [*Thouret et al., 2007*]. Overview of 108 known lahar events revealed contributions of different volcanic causative factors: pyroclastic flow (42 cases); subglacial eruptions (38 cases, not considered in this study); lava flow (6 cases of surface eruptions); and destruction of crater lakes (2 cases); genesis remained unknown in 20 cases.

The lahar hazard in onshore eruptions was evaluated according to frequency of tragic consequences in populated areas. Hot pyroclastic material that acts upon snow and ice during Plinian eruptions of andesite volcanoes turns out to be the most important agent in catastrophic scenarios: 42 cases out of the known 108 events worldwide [*Major and Newhall, 1989*]. Its damage potential is due to high-speed gravity-driven transport of pulverized magma over the surface of a volcanic edifice and above-ground surges.

Lahars associated with effusive eruptions (lava flows) occurred in 6 cases out of 108. Lava flows form during Strombolian eruptions of basaltic volcanoes. Unlike explosive eruptions, lavas erupt for longer time and flow along local troughs on steep slopes. The effect of lava on the surface of glaciers was inferred [*Pistolesi et al., 2013; Rivera et al., 2015*] to be unable of forming large volumes of water because ice melting consumes much heat and is thus slow. Note that the role of thermodynamic processes that maintain transition from surface effects to lava intrusion deep into ice and the ensuing streamflow increase were not taken into account for the lack of observations.

Eighteen lahar events observed during effusive eruptions of Kluchevskoy volcano in Kamchatka remained not included into the world catalog (their chronology was presented in [*Chernomorets and Seynova, 2010; Seynova et al., 2010*]). The amount of erupted material reached 100 million m^3, without slush flow predominant in the lahar volume [*Belousov et al., 2011; Muraviev and Klimenko, 2014*]. The mechanism of water generation in the lahar of a catastrophic eruption of Kluchevskoy will be discussed in a separate paper.

Historic records note a few lahar events at obliquely directed volcanic explosions as a result of hot tephra fallout upon ice and snow: Cotopaxi (Ecuador) in 1877; Kluchevskoy in 1945; Bezymyannyi (Kamchatka) in 1956; Saint Helens (USA) in 1980 [*Piyp, 1956; Gorshkov, 1957; Waitt et al., 1983; Muraviev and Klimenko, 2014; Pistolesi et al., 2014*]. Note that the largest lahar of 500 million m^3 in Kamchatka formed by rapid melting of snow when tephra from Bezymyannyi volcano deposited on the nearby slopes of Kluchevskoy and Ziminykh volcanoes [*Belousov et al., 2006*]. Such events recur every hundreds or thousands of years at individual volcanoes. Most often tephra falls in a cold state from very high eruptive columns, which rules out snow melting and formation of lahars [*Manville et al., 2000*].

ACTIVE SNOW- AND ICE-CLAD VOLCANOES WORLDWIDE

The role of snow and ice on volcanoes as sources of meltwater has implications for the mechanism of lahar formation. Of special interest is the global distribution of volcanoes covered with ice and snow.

Waitt et al. [*2015*] marked glacier-clad Holocene volcanoes on the World map of volcanoes from [*Venzke, 2013*], using the GLIMS glaciers database. However, they neither identified all volcanoes nor analyzed snow cover on them. Meanwhile, lahar formation mechanisms differ markedly in volcanoes covered with snow (nival-volcanic), which melts upon interaction with pyroclastic material, and with ice (glacial-volcanic), which melts on contact with lava or pyroclastics.

Although most of active volcanoes in the world are free from snow or ice and cannot induce lahars, there are provinces of high lahar hazard. We have analyzed active volcanoes in terms of the stability of snow (ice) on slopes or summits and compiled the map “Snow and ice as lahar formation factors at active volcanoes worldwide” to estimate the frequency of nival and glacial lahars.

The map was compiled using databases of volcanoes [*Venzke, 2013*], glaciers [*Arendt et al., 2015*], and snow [*Kotlyakov, 1997*], photographs from different publications, as well as climate data for some specific volcanoes. The databases were correlated and then volcanoes were identified in open high-resolution satellite images (*Google*, *Bing*, *Yandex*).

The Smithsonian Institution database [*Venzke, 2013*] contains information on more than 1500 onshore volcanoes. It was important to choose the age limit to define volcanoes as active, which remains a point of controversy. The Smithsonian database [*Venzke, 2013*] includes all Holocene volcanoes; according to another definition, active volcano is a volcano that has had known historic or documented eruptions and fumarolic or solfataric activity. However, *Melekestsev et al.* [*2001*] noted that such interpretation would impede comparison of volcanoes from different regions where available historic records may be times shorter or longer and suggested that active volcanoes are those that erupted within the past 3500 years. The latter criterion has been used in this study to select active emerged volcanoes with the age of the last eruption no older than 3500 years.

Thus we selected 668 volcanoes. Preliminary data were published in 2016 [*Belousova, 2016*], and then extended and updated.

The map of snow- and ice-clad volcanoes (Fig. 1) with insets for Alaska, Colombia, and Kamchatka shows volcanoes with and without stable snow cover, as well as those covered with both ice and snow. The map was compiled using the *ArcGIS 10.4* software in WGS-1984 coordinates, in the *Natural Earth* projection.

In some cases, data on identified glaciers and snowpacks disagree with published databases [*Arendt et al., 2015*] and with studies of snow, ice and glaciers [*Singh et al., 2011*]. For instance, volcanoes from the Aleutian Islands poorly studied in terms of glaciation (Tanaga, Takawangha, Kiska, Carlisle, Cleveland, Ugashik-Peulik, etc.) were selected or not proceeding from deciphered signatures of glaciers.

Furthermore, data on the age of the latest eruptions are controversial for some volcanoes. For instance, according to the database of *Venzke* [*2013*], Mount Kazbek volcano (Caucasus Mountains) erupted in 750 BC but radiocarbon dates (obtained at the Tbilisi State University, Tbilisi, and at the Institute of Mineral Geology, Petrography, Mineralogy and Geochemsitry, Moscow) record the latest eruption about 6000 years ago, from a side cone of Small Tkarsheti below the elevation of the present glaciers rather than from the ice-capped summit of Mt. Kazbek [*Burchuladze et al., 1976; Chernyshev et al., 2002; Lebedev et al., 2014*]. On the other hand, a discussion arose about volcanic heating and fumarolic activity as agents in the Kolka glacier catastrophic surge of 2002 in the Karmadon Gorge [*Muraviev, 2005*] and the surge of the Devdoraki Glacier in 2014 [*Chernomorets, 2014*]. Finally, we decided to keep Mt. Kazbek in the list of active glacier-clad volcanoes.

Some volcanoes in Kamchatka (e.g., Alnei, Gorny Institut) fall outside the list of active volcanoes made by local volcanologists [*Fedotov and Masurenkov, 1991; Melekestsev et al., 2001*], but they should be on our list according to the time of their latest eruption.

When selecting emerged volcanoes, we took into account the fact that some volcanic edifices became temporally emerged by submarine eruptions but were eroded later. Only the volcanoes that remain emerged at the present were kept on the list.

Unlike glaciers which can be located with certitude, except for few cases, snowpacks have less distinct contours. We tried to select volcanoes where a stable snow cover forms almost yearly. Volcanoes with stable snow cover were selected using maps of snow maximum [*Kotlyakov, 1997*], while those without stable snow cover had to have at least 25 mm of snow (in water equivalent) required for lahar formation.

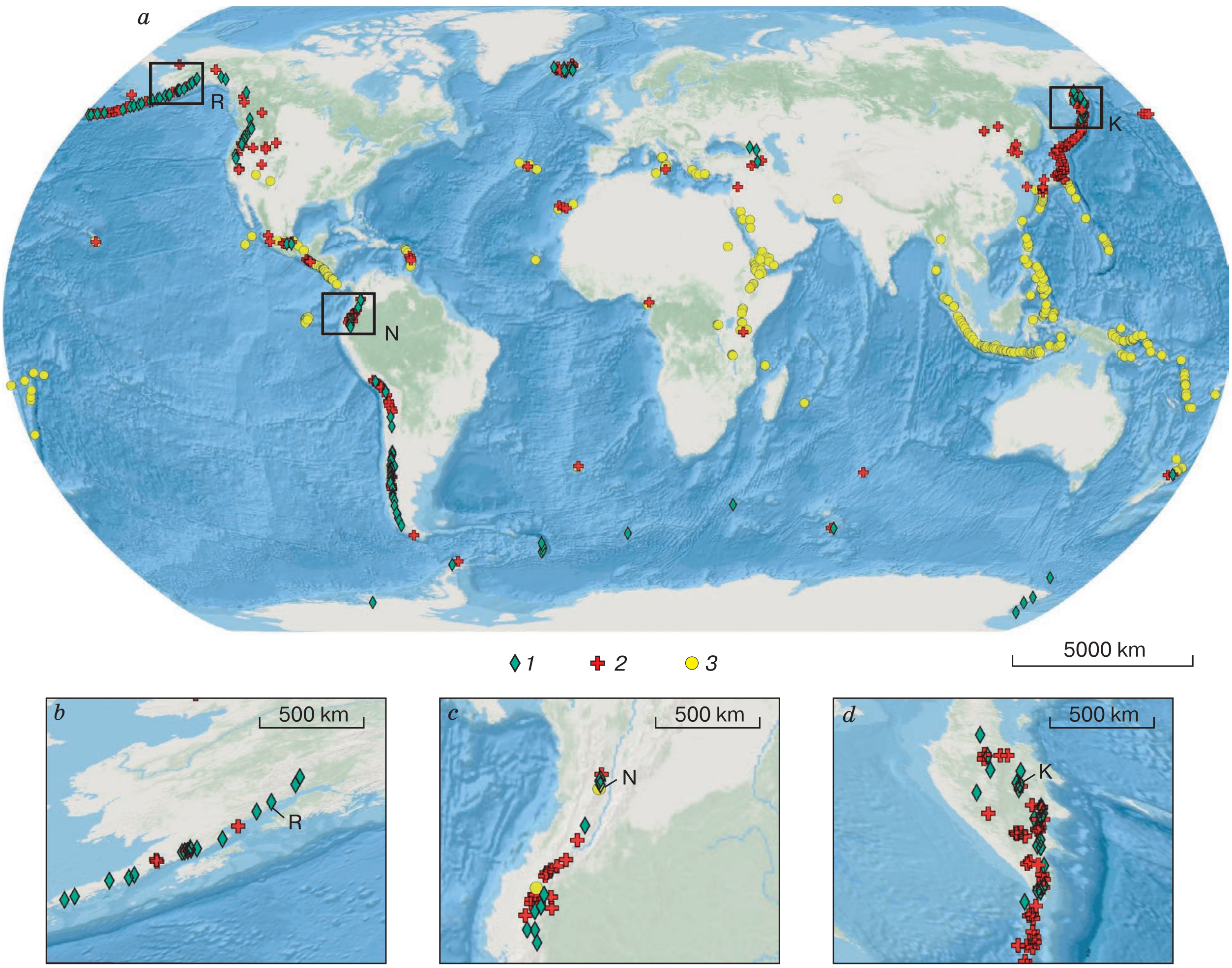

Fig. 1. Active volcanoes of the world with stable snow cover and/or glaciers.

a: world as a whole, *b*: Alaska, *c*: northern Andes, *d*: Kamchatka and northern Kuriles.
1 – volcanoes with glaciers, *2* – volcanoes with stable snow cover, *3* – volcanoes without stable snow cover; R = Redoubt, N = Nevado del Ruiz, K = Kluchevskoy. *Natural Earth* projection.

Table 1. **Glacier-clad active volcanoes of the world as potential lahar hazard sites**

Volcanic	Glacier-clad volcanoes	
	Number	Name
Kamchatka and Kurile Islands	21	Alaid, Alney, Avachinsky, Gamchen, Gorny Institute, Ichinsky, Kambalny, Klyuchevskoy, Koryaksky, Koshelev, Krasheninnikov, Kronotsky, Mutnovsky, Severny, Sheveluch, Taunshits, Tolbachik, Ushkovsky, Vysoky, Zheltovsky, Zhupanovsky
Alaska	31	Akutan, Aniakchak, Atka, Chiginagak, Churchill, Dana, Fourpeaked, Gareloi, Great Sitkin, Griggs, Hayes, Iliamna, Katmai, Korovin, Kupreanof, Mageik, Makushin, Martin, Pavlof, Redoubt, Shishaldin, Snowy Mountain, Spurr, Takawangha, Tanaga, Trident, Westdahl, Wrangell, Veniaminof, Vsevidof, Yantarni
Canada, western USA and Mexico	14	Adams, Baker, Edziza, Glacier Peak, Jefferson, Hood, Lassen Peak, Meager, Pico de Orizaba, Popocatépetl, Rainier, Shasta, St. Helens, Three Sisters
Northern Andes (Colombia, Ecuador, Peru)	11	Antisana, Cayambe, Chimborazo, Cotopaxi, Nevado del Huila, Nevado del Ruiz, Nevado del Tolima, Sabancaya, Sangay, Santa Isabel, Tungurahua
Southern Andes (Argentina, Chile, Bolivia)	39	Aguilera, Antillanca Group, Antuco, Arenales, Calbuco, Callaqui, Cerro Hudson, Copahue, Descabezado Grande, Guallatiri, Lanín, Lautaro, Llaima, Llullaillaco, Lonquimay, Maca, Maipo, Melimoyu, Mentolat, Michinmahuida, Mocho-Choshuenco, Monte Burney, Nevados de Chillán, Nevados Ojos del Salado, Osorno, Parinacota, Planchón-Peteroa, Puntiagudo-Cordón Cenizos, Puyehue-Cordón Caulle, Quetrupillán, Reclus, San José, Sollipulli, Tinguiririca, Tromen, Tupungatito, Viedma, Villarrica, Yate
Southern Atlantic Ocean, Indian Ocean and Pacific Ocean (including New Zealand)	11	Bouvet, Heard, Bristol Island, Buckle Island, Candlemas Island, Deception Island, Marion Island, Montagu Island, Ruapehu, Saunders, Southern Thule
Antarctica	4	Erebus, Hudson Mountains, Melbourne, Pleiades
Caucasus	3	Ararat, Elbrus, Kazbek
Iceland	10	Bárðarbunga, Eyjafjallajökull, Grímsvötn, Hekla, Katla, Kverkfjöll, Langjökull, Öræfajökull, Snæfellsjökull, Torfajökull
Total	144	

The 25 mm limit was used to classify volcanoes in southern Japan (map of snow compiled by T. Glazovskaya and A. Glazovskiy). In the absence of maps or in case of doubt, we used climate data from nearby weather stations, specifically, for some volcanoes in Central America and oceanic areas (the islands of Azores). To confirm our inferences, we searched available photographs showing snowpacks and glaciers on respective volcanoes.

Out of 668 volcanoes in the map, 298 (44 %) have no stable snow cover; 226 (34 %) are periodically covered with snow; and 144 (22 %) are ice-capped (Fig. 1). There are two main trends in the distribution of snow- and ice-covered volcanoes. The number of volcanoes with snow and then with ice increases toward high latitudes (distinct latitude zoning). Glaciers occur on volcanoes of Kamchatka, Alaska, western North and South Americas, Antarctica, Iceland, and some high-latitude islands. On the other hand, there is altitude zoning: glaciers exist on the highest volcanoes even near the equator (e.g., Nevado del Ruiz in the Andes).

Table 1 shows a list of active glacier-clad volcanoes in different volcanic provinces of the world. Ice can lie on the summit, on the slopes, or at the foot of volcanic edifices. Photographs of some ice-capped volcanoes taken from the international space station are presented in Fig. 2.

Types of volcanoes are also important for lahar hazard estimation: stratovolcanoes are the most hazardous in this respect. Most of glacier-clad volcanoes belong to this type (118 out of 144 volcanoes, or 82 %); the others are shield, subglacial, caldera volcanoes, etc.

Most of ice- and snow-clad volcanoes are located in the USA (41), Chile (37), and Russia (24); some volcanoes belong to these countries only partly, being located at national frontiers.

FORMATION OF MELTWATER FLOW BY VOLCANO-ICE INTERACTION

Formation of water flow in lahars during eruptions of glacier-clad volcanoes was studied for the case of the Nevado del Ruiz event of November 13, 1985 in Colombia which killed about 23,000 people [*Lowe et al., 1986; Pierson et al., 1990; Thouret, 1990; Thouret et al., 2007*]. Lahars originated on the ice cap of the volcano, at the source of the Azufrado and Lagunillas rivers, and traveled 65 km to Armero town for 2 hours. The lahar paths (Fig. 3) were reconstructed based on published evidence.

The first surge was clear and cold water that flooded the vicinity of a protective drainage channel in Armero town while a catastrophic mudflow rushed on the town ten minutes later. The surge reaching 5 m high flooded most of the town in 20 minutes (from 11:35 to 11:55 pm). The final phase of debris

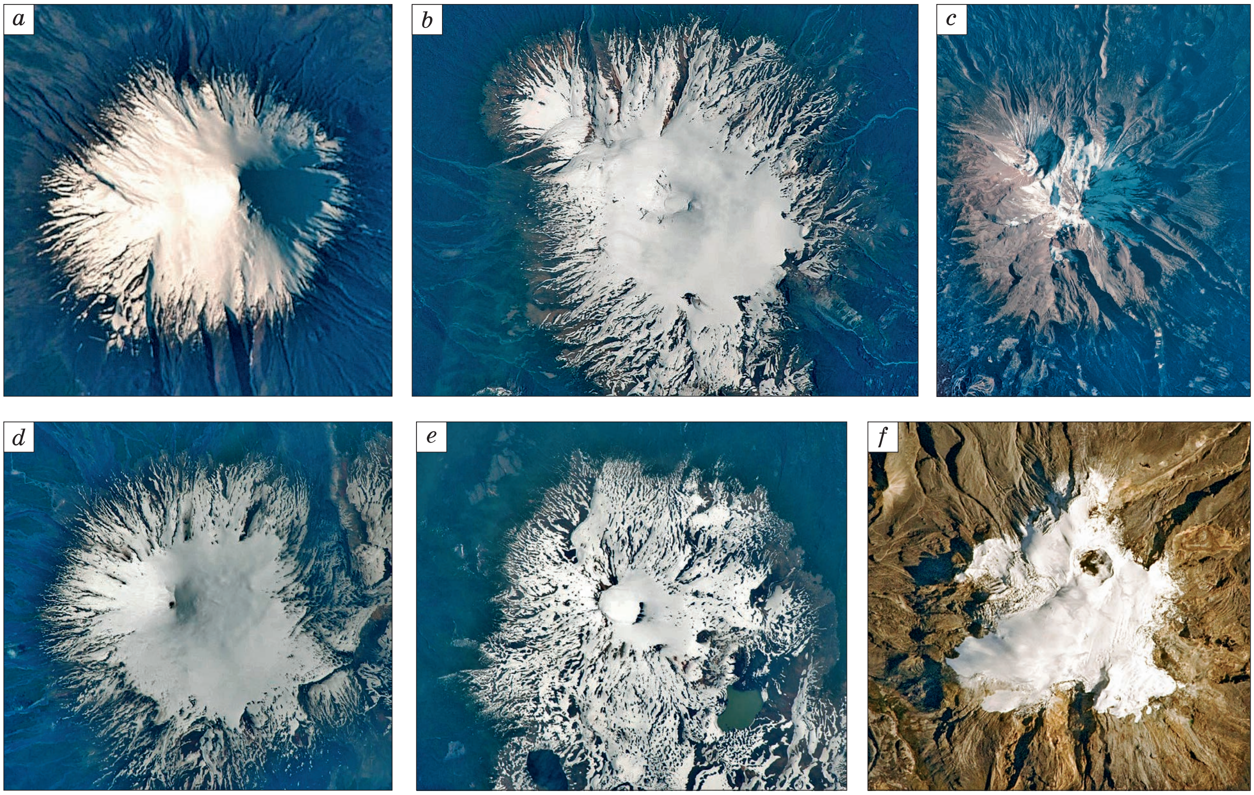

Fig. 2. Some active glacier-clad volcanoes.

a: Osorno (Chile); *b*: Mocho-Choshuenco (Chile); *c*: Shasta (US); *d*: Villarrica (Chile); *e*: Quetrupillán (Chile); *f*: Nevado del Ruiz (Colombia). Photographs shot from an international space station, by S. Ryazanskiy (*a–e*, November 16 and 21, 2013, 37-th mission, *Uragan* Program, courtesy of S. Ryazanskiy) and by NASA specialists (*f*, April 23, 2010, 23-rd mission, courtesy of NASA).

flood lasted all over the night of November 14, and spared only a small part of the town (Fig. 4). The lahars raced into the Chinchiná and Gualí Rivers and reached the towns of Mariquita and Honda located 78 km and 96 km away from the volcano, respectively, and Chinchiná town (43 km far from volcano), where about 2,000 people were killed and hundreds of houses were destroyed [*Pierson et al., 1990*].

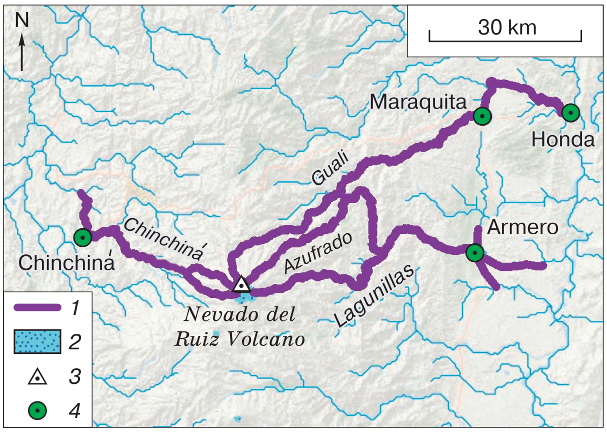

Fig. 3. Lahars generated by the Nevado del Ruiz eruption of November 13, 1985.

1 – lahar paths; *2* – glaciers; *3* – summit of volcano; *4* – towns.

Fig. 4. Armero town on a fan of the Lagunillas River was buried under a lahar on November 13, 1985.

On the right: Only a few buildings and structures survived [*Pierson et al., 1990*].

The summit of Nevado del Ruiz, 5389 m asl, was capped by 25 km^2 of ice [*Thouret, 1990*]. The eruption began with an explosion at 8:08 pm, and the collapse of the eruptive column produced a hot pyroclastic flow of ten million m^3, which is a common magnitude for Plinian-type eruptions. Melting of ice and snow under hot debris caused 10 % reduction of the ice cap having released ninety million m^3 of meltwater, and thus induced several lahars flowing down the rivers of the northeastern volcano slope. Interactions between eruption products (especially pyroclastic density currents) and ice or snow caps are the key to the paradox explaining why a small eruption could lead to a great volcanic disaster [*Pierson et al., 1990*]. The pyroclastic flow system comprises solid material (density currents) upon the ground and a surge rising above the ground. The two components have different mechanisms of volcano-ice interaction responsible for the lahar formation.

PYROCLASTIC SURGE

Pyroclastic surge is the major agent inducing water flow in lahars. Such a surge swept off all ice from the north-western slope of Nevado del Ruiz for first twenty minutes of eruption and generated up to six or seven million cubic meters of slush at the Azufrado and Lagunillas headwaters, which transformed into liquid water [*Thouret et al., 1990*]. The key role of pyroclastic material in the formation of slush flow, the precursor of mud and debris flows, was also reported for Saint Helens (USA) and Cotopaxi (Ecuador) volcanoes that erupted in 1980–1983 and 1995–1996, respectively [*Waitt, 1989; Pistolesi et al., 2013*]. During explosion of Mt. Saint Helens in May 1980, slush flows raced down gullies into rivers and turned into a giant 10 million m^3 lahar moving down the Toutle River [*Fairchild, 1987*]. The water component in the lahar of the Shiveluch eruption (Kamchatka) on April 2012 formed by rapid melting of snow heated by pyroclastic surge [*Seynova et al., 2014*].

Field and laboratory experiments showed that kinetic energy and heat from low-density pyroclastic surge cause sublimation and softening of snow to a depth <2 m. Instability of the released steam induces convective mixing of hot debris and snow into a slush. Further loading upon dense snow and firn triggers avalanches and downslope flows of slush [*Fairchild, 1987; Manville et al., 2000*]. Dilute flows and avalanches rapidly transform into debris flows in river channels by entrainment of sediment and thus increase greatly the lahar volume [*Waitt et al., 1983; Pierson, 1985; Scott, 1988; Waitt, 1989; Pierson et al., 1990; Cronin et al., 1996*].

PYROCLASTIC DENSITY CURRENTS

Pyroclastic density currents contact glacier ice directly after the snow cover has been swept off. Hot pyroclastic material scours the ice and causes voluminous meltwater flow [*Waitt, 1989*]. As shown by processing of field data after the catastrophic lahar event of November 13, 1985, 80 % of its 43 million m^3 streamflow consisted of glacier meltwater.

Pyroclastic flows produced up to 100 m wide and 2–4 m deep scours on the ice cover of Nevado del Ruiz volcano. The brief impact of pyroclastics on the ice-snow cover, indicated by large width of the scours, transformed hot volcanic material into a mixture of water, debris, sand, and ash within the glacier limits. This mixture constituted the enormous mud-debris phase of the lahar. In the same way, pyroclastic density currents ploughed up to 50 m deep troughs in ice during the eruptions of Villarrica (Chile, 1877) and Redoubt (Alaska, 1989) [*Roach et al., 1996; Rivera et al., 2015*] (Fig. 5). Different panels of Fig. 5 show effects of the Redoubt eruption of 1989–1990: an ice canyon ripped by pyroclastic flow (*a*); the Drift River valley with traces of lahars (*b*), a map of lahar paths (*c*), and *Landsat* images shot before and after the event (*d*, *e*, respectively).

The effect of hot pyrocalstic flow on glaciers is largely due to turbulent heat transfer in transverse speed pulses. The turbulence extends the surface area of debris-ice (snow) contact and favors the penetration of heat inward the glacier. Intense mixing accelerates heat and mass transfer and makes it more active than in the case of static heat conduction. Experiments show that the ice melting rate during turbulent heat transfer is 60 times faster than melting under a cover of volcanic products. Thus the discharge capacity of the drainage network increases and water flow enhances at the account of intraglacier waters. Thermodynamic erosion by pyroclastic flow is sufficient for producing tens of million cubic meters of meltwater for a few minutes [*Pierson et al., 1990; Thouret et al., 2007*].

STATIC MELTING OF ICE UNDER ERUPTION PRODUCTS

Ice melting under deposited magma is slower than the thermodynamic effect from a moving flow. Passive heat transfer from hot material to a glacier below it can produce a 33–46 mm thick molten layer for 30 minutes. The meltwater flow from Nevado del Ruiz during the post-catastrophic lahar phase for the night of 14 November 1985 resulted from static melting of low-angle glacier parts under residual deposits of hot pyroclastics [*Pierson et al., 1990*].

The total annual amount of water generated by the volcano-ice interaction at Nevado del Ruiz reached 43.6 million m^3 (summed data from individual valleys reported by *Pierson et al.* [*1990*]). The lahar volume enhanced at the account of erosion and sediment mobilization in rivers to 70–190 million m^3 [*Huggel et al., 2007*] and largely exceeded the original water pulse.

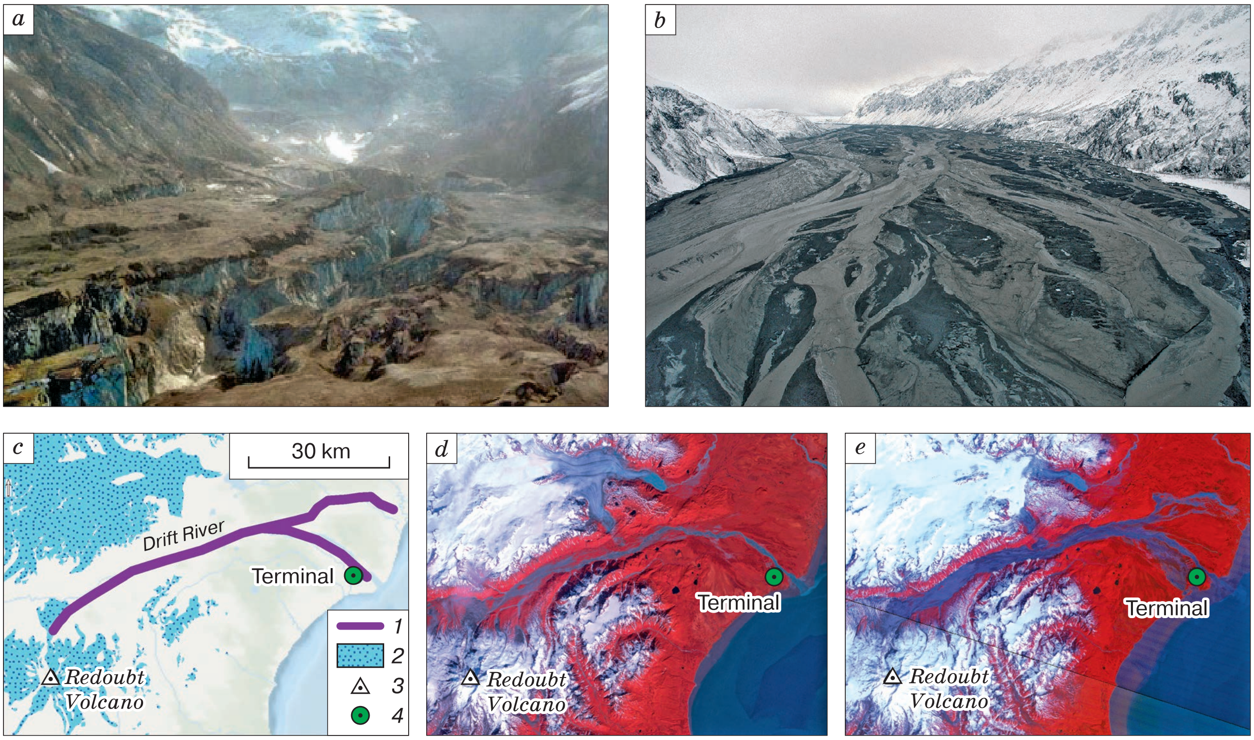

Fig. 5. Lahars during eruptions of Redoubt volcano (Alaska, USA).

a: ice canyon at lahar origin produced by pyroclastic flow upon a glacier during the eruption of 1989–1990. Photograph by T. Miller, US Geological Survey, April 1990 [*Roach et al., 1996*]; *b*: lahar-affected zones in the Drift River Valley (1989–1990 and 2009). Photograph by R. McGimsey, 23.03.2009 [*McGimsey, 2009*]; *c*: map (*1* – lahar paths, *2* – glaciers, *3* – summit of volcano, *4* – industrial object); *d* – volcano before eruption, *Landsat-5* image of 21.08.1987; *e*: volcano after eruption, *Landsat-4* image of 30.06.1992.

CONCLUSIONS

According to the review of open databases on volcanism, existing glaciers, and snow cover on volcanoes, we selected 144 glacier-clad volcanoes, 226 volcanoes with a stable annual snow cover, and 298 volcanoes free from annual snow.

Investigation into catastrophic lahars associated with eruptions of onshore glacier-clad volcanoes worldwide revealed main mechanisms of water flow generation by volcano-ice interaction:

– melting of snow mixed convectively with material of pyroclastic surge and hot tephra;

– ice fracture and melting by thermodynamic effects of pyroclastic flows upon glaciers;

– melting of glaciers by thermodynamic effects of lava flows;

– melting of glaciers by conductive heat transfer from deposited eruption products.

The compiled map of glacier-clad volcanoes of the world spots the sites of potential lahar hazard for further studies.

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