Chapter

Catastrophic Processes in River Valleys of Volcanic Regions: Geomorphologist's Point of View

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Abstract

The river valleys located in volcanic regions are prone to various catastrophic processes, including those catalyzed by eruptions. First, to be mentioned among them are volcanic mudflows known as lahars. They commonly result from melting of ice, snow on the mountaintop, and rainfalls immediately following the eruption. This sequence of catastrophic events—"eruption-volcanic mudflow"—is quite common and has been well studied. When viewed closely the mud and debris flow in the volcanic regions appears to be brought on by various causes, with many factors and agents involved. Quite commonly, an eruption triggers not a single endo- or exogenic event, but a sequence of interrelated catastrophes following one after another. The studied cases allow identifying and describing up to two tens of probable scenarios—successions of catastrophic events in river valleys of the volcanic regions. The specific chain in any particular case depends on volcanic activities and accompanying events, such as seismic shocks, changes in local topography, hydrothermal activity, and erosion. The river valleys and adjoining areas are the most hazardous and vulnerable areas within as much as a few kilometers from the eruption center as the erupted material tends to accumulate in valleys and rapidly transported downstream.

Keywords: lava flow, pyroclastic material, gas-hydrothermal manifestations, valley infilling, dammed lake, mudflow, river network restructuring

1. Introduction

Catastrophic geomorphic processes in river valleys of volcanic regions (as well as in nonvolcanic ones) may result from various natural events, such as floods due to high-intensity rains, fast snow melting, or a water breakthrough from lake dammed by landslide or rockfall bodies. The areas of the present-day volcanicity are distinct for yet another catastrophe catalyst in river valleys: endogenic factor, primarily volcanic eruptions. The latter are often responsible for the descent of volcanic mudflows—lahars—related to melting of glaciers, snow caps on the volcanic

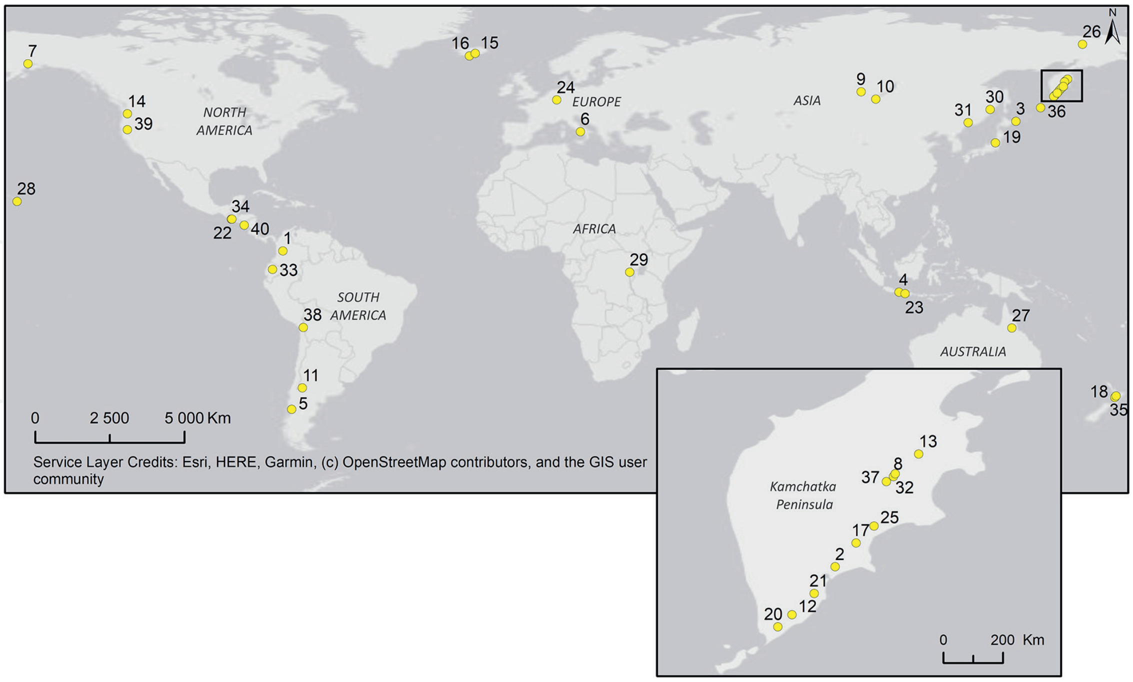

Figure 1.
Location of the volcanoes, mountains, and other objects described in this paper (yellow circles; numbering corresponds to the mentioned order in the text): 1 - Nevado del Ruiz volcano (vlc.), Columbia; 2 - Avachinsky vlc., Kamchatka, Russia; 3 - Mendeleev vlc., Kunashir Isl., Russia; 4 - Merapi vlc., Indonesia; 5 - Chaiten vlc., Chile; 6 - Vesuvius vlc., Italy; 7 - Spurr vlc., Alaska, USA; 8 - Bezymyanny vlc., Kamchatka, Russia; 9 - Eastern Sayan Mountains (Mnts.), East Siberia, Russia; 10 - Khamar-Daban Mnts., East Siberia, Russia; 11 - Pampas Onduladas lava flow, Mendoza, Argentina; 12 - Ksudach caldera, Kamchatka, Russia; 13 - Shiveluch vlc., Kamchatka, Russia; 14 - St. Helens vlc., Washington, USA; 15 - Grimsvötn vlc., Iceland; 16 - Katla vlc., Iceland; 17 - Akademia Nauk caldera, Kamchatka, Russia; 18 - Ruapehu vlc., New Zealand; 19 – Numazawa vlc., Japan; 20 - Kuril Lake caldera, Kamchatka, Russia; 21 - Mutnovsky vlc., Kamchatka, Russia; 22 - Agua vlc., Guatemala; 23 - Kelud vlc., Indonesia; 24 – Laachen see vlc., Germany; 25 - Uson-Geysernaya caldera, Kamchatka, Russia; 26 - Anyuyskiy vlc., Chukotka, Russia; 27 - Undara lava flow, Queensland, Australia; 28 - Hawaiian islands, USA; 29 - east African rift zone (Nyiragongo vlc., Congo); 30 - Sikhote-Alin' Mnts., Far East, Russia; 31 - East Manchurian Mnts., Far East, Russia; 32 - Klyuchevskoy vlc., Kamchatka, Russia; 33 - Cotopaxi vlc., Ecuador; 34 - Fuego vlc., Guatemala; 35 - Taupo volcanic zone, New Zealand; 36 - Sarychev peak vlc., Matua Isl., Russia; 37 - Tolbachik vlc., Kamchatka, Russia; 38 - Parinacota vlc., Chile; 39 - Shasta vlc., California, USA; 40 - Casita vlc., Nicaragua.

cones, or abundant rainfalls. Among them, there is a notorious lahar developed at the Nevado del Ruiz volcano eruption in Columbia (**Figure 1**) in 1985 and killing 23,000 people [1].

As summarized by Ref. [2], more than 200 million people are living in settlements within 200 km distance from active or potentially active volcanoes, that is, within the zones of immediate danger. Most of the towns and settlements within that zone are either confined to river valleys or located in close vicinity to them. As seen from the statistics cited by the specialist, 17% of human deaths during the eruptions result from lahars that occur typically in the river valleys, and another 27% from the pyroclastic flow, the maximum thickness of the latter being usually confined to topographic lows. So, the maps of endangered areas show as a rule river valleys and adjoining territories as the most hazardous, even in case they are at a considerable distance from volcanoes, see maps of volcanic regions Avachinsky [3] and Mendeleev [4] volcanoes (Kuril-Kamchatka region of Russia - See **Figure 1**), Merapi (Indonesia) [5], and many others (**Figure 2**). A good example is Chaiten town (Chile) partially destroyed because of the descent of the lahars along the Blanca River valley in

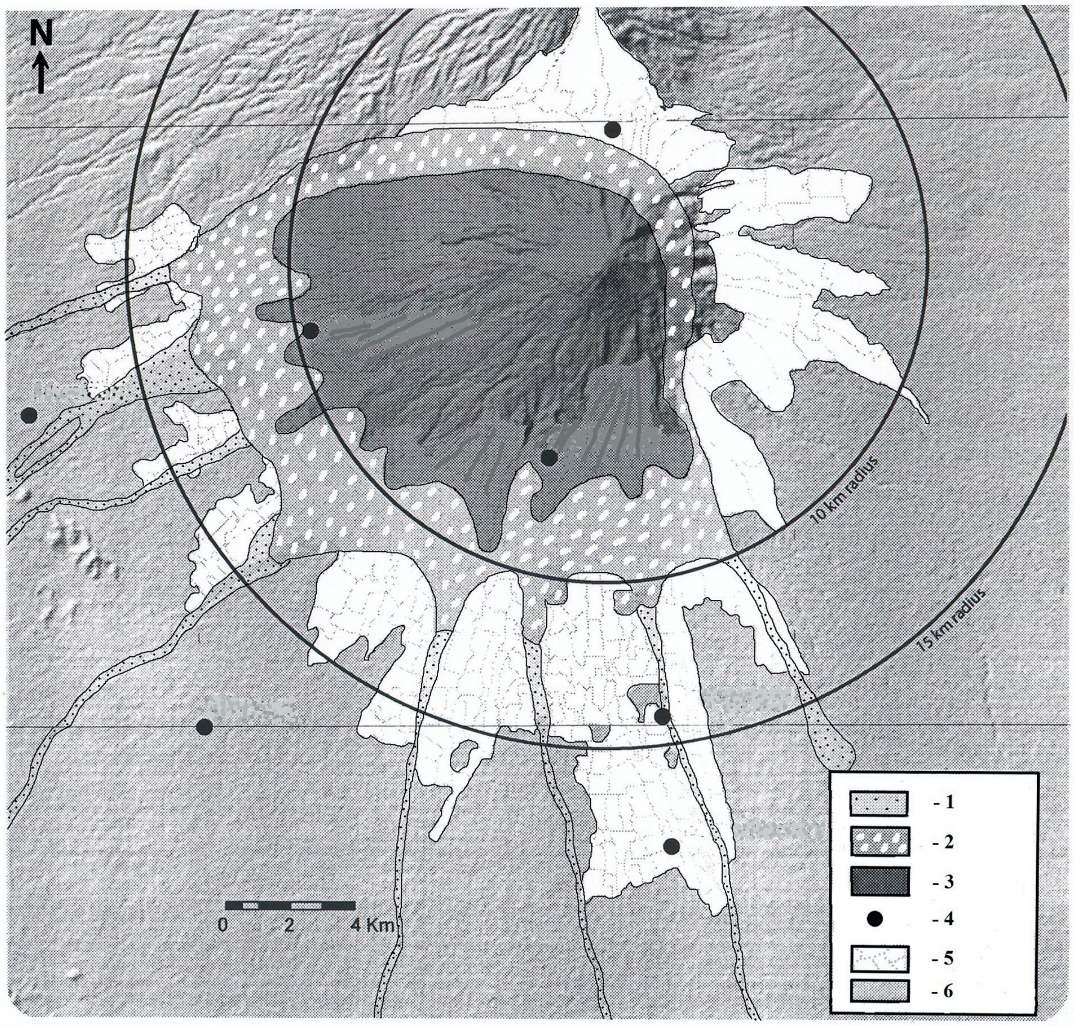

Figure 2.
Schematic map of volcanoes impact zones: 1 - river valleys originating on the volcano: Lahars, floods, and pyroclastic flow dominate; 2 - volcano foot: Pyroclastic flows, hot avalanches and lahars, lava flows, and toxic gas emissions dominate; 3 - volcano slopes: Frequent impact of pyroclastic and lava flows, rockfalls, toxic gas emissions, and formation of extrusive domes; 4 - settlements; 5 - agricultural land; and 6 - forests.

Figure 3.
The Chaiten town (Chile) was demolished by lahars in 2008–2009 after Chaiten volcano eruption (see ***Figure 1****, No 5). Buildings on the Blanco river banks: A - left bank, b - right bank. White arrow—Lahar deposits (2010, here and thereafter all photos are courtesy of the author unless stated otherwise).*

2008–2009 during the Chaiten volcano eruption. The areas of the town directly adjacent to the river suffered the most (**Figure 3**). Areas closer to the volcano but further from the river were only partially covered with ash.

The sequence of catastrophic events—"eruption-volcanic mudflow (lahar) descent" is well studied and quite common [2, 6–12], etc. To take one example, A. Neri and his colleagues [13] considered 12 scenarios of potential eruptions of Vesuvius volcano different in type and the subsequent development of catastrophic processes on its slopes; the specialists arrived at the conclusion on the probable lahar descent in eight cases. There is a commonly accepted distinction made between primary (or hot) mudflows immediately following the eruption and secondary (cold) ones that may occur a few decades after it. It should be noted that mudflows could form even on the slopes of extinct volcanoes under favorable conditions (steep slopes, loose material abundance, etc.).

When viewed more closely, the catastrophic processes in river valleys of volcanic regions display a considerable diversity of factors accountable for mudflow formation; besides, the spectrum of hazards is notably wide. Quite frequently, an endogenic event—an eruption—entails not a single catastrophic (endo- or exogenic) process, but a series of interrelated and sequentially developing catastrophes, that is, a cascade of hazardous processes.

Good examples are described in Ref. [14], where lahars associated with 1953 and 1992 eruptions of the Spurr volcanic complex descending along Crater Peak Creek (Chakachatna River tributary, Alaska, USA—— see **Figure 1**) blocked the main river with the formation of dammed lakes of quite impressive volumes (from 3.2 to 12 x 10^7 m^3). The destruction of temporary dams and the descent of lakes led to debris flows. The author concludes that the formation and failure of debris dams is a common process in this river valley and a consequence of pyroclastic eruptions of the Spurr volcanic complex.

This work is aimed at the analysis of the causes and subsequence of the hazardous phenomena in river valleys of the volcanic regions with different types of volcanic and post-volcanic activity. The methodology used is based on a thorough analysis of high and ultra-high-resolution satellite images followed by field geomorphological observations, including the study of the relief and geological structure of the territory, loose sediments, and bedrock. In key areas, a morphometric analysis of the longitudinal and transverse profiles of the valleys was carried out, and deposits of lahars and mudflows, dammed lakes, fragments of destroyed dams, and their genesis were studied. An important stage was the critical analysis of literary sources. The identification of connections and interdependencies of geological phenomena and chains of catastrophic geomorphological processes under conditions of the dominance of various types of volcanism—effusive, explosive, volcano-tectonic phenomena, and gas-hydrothermal processes—made it possible to create a classification scheme of catastrophic processes in volcanic regions river valleys. In the process of creating the scheme, the types of predominant volcanism, the nature of the volcanic material and the types of its movement, concomitant factors, and the sequence of catastrophes were identified. The cases studied by the author during her geomorphologic field survey in the volcanic regions of Russia and abroad as well as the literature analysis made it possible to identify up to two tens probable scenarios—successions of catastrophic events in river valleys (**Table 1**). In every case, the type of endogenic factor and specific features of its manifestation were taken into consideration, along with specific environmental characteristics (geology and geomorphology, hydrology, climate, and glaciation). The results may be important for the purpose of forecasting dangerous event, and for protecting people against endogenic natural disasters.

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Endogenic factors	**Additional factors**	**Succession of catastrophic events**			**Specific case**
		1	**2**	**3**	
Effusive or explosive eruption	Presence of (a) glaciers, (b) snow cover, or (c) abundant rainfall	Volcanic mudflows (lahars) in the main valley	—	—	a) Nevado del Ruiz vlc. (1985), Columbia b) Bezymyanny vlc.(1956), Kamchatka, Russia c) Chaiten vlc. (2008–2009), Chile
		Lahar flow along the tributary	The main valley is dammed by lahar, lake develop	Dammed lake outburst—mudflow descent	Spurr vlc. (1953, 1992), Alaska (Crater Peak Creek - Chakachatna R.)
Effusive eruption	Lava flow movement along the valley	The valley is filled with lava	The upstream part of the main valley and those of tributaries are flooded	Dam breach or spillover of dammed lake—mudflow descent	Maly Yenisey R., Jom-Bolok R., Eastern Sayan, Russia; Hvítá R., Iceland
	Lava flow movement across the valley	The valley is dammed by lava	Flooding of the valley upstream from the dam	Dam failure — mudflow descent	Dzhida R., Khamar-Daban, Oka R., Eastern Sayan, Russia; Colorado R., Mendoza, Argentina

Endogenic factors	Additional factors	Succession of catastrophic events			Specific case
		1	2	3	
Explosive eruption	Breakdown of the uppermost part of the volcanic cone	The valley is dammed by large fragments of the cone	The upstream part of the valley is flooded, the dammed lake level rises	Dam failure—mudflow descent	Teplaya R., Shtyubel cone (1907), Ksudach caldera, Kamchatka, Russia
	Breakdown of one side of the cone-sector collapse	Debris avalanche formed	Pyroclasts build up and fill valleys	Erosion of pyroclasts and mudflows formation	Bezymyanny vlc.(1956), Shiveluch vlc. (1964), Kamchatka, Russia
			Dams are built and dammed lakes develop upstream	Dammed lake outburst—mudflow descent	Chakachatna R., Spurr vlc. Complex, Alaska; St. Helens vlc. (1980), USA
	Pyroclastic flow descent	Valley is filled with pyroclastic material	Erosion of pyroclast contributes to mudflow development.	—	Kabeku R., Shiveluch vlc. (2010), Kamchatka, Russia
			Tributary mouths are dammed, and lakes develop	Dammed lake outburst—mudflow descent	Bekesh R., Shiveluch vlc. (2010), Kamchatka, Russia
	Pyroclastic mantle formation	Pyroclasts more than 1 m thick accumulates in the region of eruption	Pyroclasts move downslope to the valley floor	Mudflows result from rainfall and snow melting	Shtyubel cone (1907), Ksudach caldera, Kamchatka, Russia
Subglacial eruption	The ice sheets or well-developed alpine glaciers	Subglacial lake formation, the ice surface subsidence	Glacial outburst flood (jökulhlaup)	—	Grimsvötn vlc. (1996), Katla vlc. (1918), Iceland
Underwater / above water eruption	Lake in the immediate vicinity of the eruption center	The rise of tsunami or ejected water	The lake expulsion and the mudflows descent down the river flowing out of the lake	—	Karymsky R., Karymsky Lake (1996), Academia Nauk caldera, Kamchatka, Russia; Crater Lake, Ruapehu vlc., New Zealand

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Endogenic factors	Additional factors	Succession of catastrophic events			Specific case
		1	2	3	
Volcano-tectonic activities	Collapse caldera formation	Partial destruction of the river valley filled with pyroclasts	Enhanced downcutting upstream, mudflow descent	—	Streams in the Ksudach caldera, Kamchatka, Russia
		The valleys are filled with pyroclasts, including ignimbrites	River damming and lake formation	Dammed lake expulsion—mudflow descent	Tadami R., Numazawa vlc., Japan
	Change in the surface slope: a dome growth in the river basin, local subsidence, and fissures.	Changes in the river's long profile—partial inundation of the valley	Water overflow from the lake—mudflow descent	—	Lagernyi creek, Shtyubel cone, Ksudach caldera, Kamchatka, Russia
	Rapid extrusion growth	Huge rockfall or debris avalanche	River damming and lake formation	Dammed lake expulsion—mudflow descent	Ozernaya R., Dikyi Greben' extrusion, Kuril Lake caldera, Kamchatka, Russia
Seismic events	Densely fissured zone, hydrothermal alteration, loose deposits, and heavy rains	The mass movement downslope (landslide, slump) blocks the valley	Descent of mudflow (removal of material brought downslope)	Partial inundation of valley, dammed lake formation; mudflow at the lake expulsion	Fal'shivaya R. tributaries, Mutnovsky vlc., Kamchatka, Russia
		Crater wall breakdown, and overspill	Mudflow descent	—	Agua vlc. (1541), Guatemala; Kelud vlc. (1875), Indonesia
		Dam failure	Mudflow descent		Laacher See vlc., Germany
Gas-hydrothermal manifestations	Steep river valley slopes, sometime rainfall or weak earthquake impact	Landslide or rockfall	Mudflow descent	—	Geysernaya R. (1982), Uzon-Geysernaya caldera, Kamchatka, Russia
		Landslide or rockfall blocking the valley	Mudflow descent, dammed lake formation	Mudflow at the lake expulsion	Geysernaya R. (2007, 2014), Uzon-Geysernaya caldera, Kamchatka, Russia

Table 1.
Catastrophic processes in river valleys of volcanic regions.

2. Chains of catastrophic events in river valleys of volcanic regions

The river valleys in volcanic regions often originate on slopes of volcanic cones. In their uppermost reaches, they have a look of erosional hollows ("barrancos" in Spanish). If a river flows in a fault zone with eruption centers of its own (moderate-size shield volcanoes), the latter appears to be within the valley itself. Such phenomena may be seen, for example, in the upper reaches of the Bolshoy and Maly Yenisey, in the Jom-Bolok (Zhom-Bolok) river valley in the Eastern Sayan mountains (Southern Baikal volcanic region, Russia) [15–17], in the Bolshoy Anyuy river valley in Chukotka (the Northeast of Russia—see **Figure 1**) [18].

In either case, an *effusive eruption* may result in the river valley being filled with lava flow, sometimes over a length of tens and even more than one hundred kilometers. The basalt flows of the Middle Pleistocene age—among them Undara (Queensland, Australia) and Pampas Onduladas (Mendoza, Argentina), both up to 160–170 km long are recognized as the longest-**Figure 1**) [19, 20]. There is a lava flow which is greater in size in the Maly Yenisey river valley (Eastern Sayan mountains, Russia)—it is 175 km long, up to 1.5 km wide, and its volume is estimated at 40–50 km^3 [16]. The youngest basalt flow comparable to the above-named in length (~140 km) is Thjorsa (Þjorsa, Iceland) [21] dated to the Holocene. Another lava flow of young age (about 13 ka BP) is the Jom-Bolok (Eastern Sayan mountains, Russia—see **Figure 1**) [22, 23]: it is 70 km long, up to 2 km wide, and as much as 150 m thick. The formation of flows of such a length is possible during the outpouring of liquid basaltic lavas and at significant flow rates. It is known that, for example, in the recent eruptions on the Hawaiian islands and in the east African zift Zone (Congo) the lava flows moved at a rate of 40 and up to 100 km per hour [2].

Under conditions of a heavily dissected topography, lava flows tend to fill river valleys. In case the land surface is relatively flattened, the lava flow may be inconsistent with valley direction, as we can see with Undara (Queensland, Australia) and Thjorsa (Iceland) basalt flows [19, 21]. Lavas may flow across flat-bottomed shallow linear hollows, cover low watersheds, and form dams of a kind; as a result, the river appears completely dammed or its flow is forced aside. A phenomenon of that type has been described in the Colorado river valley (Mendoza province, Argentina), where El Corcovo lava flow blocked the river ~840 ka BP; later the stream formed a new incision about 1 km south of its former position [24].

As to morphologically distinct valleys, they may be completely or partially filled with lava, with both mainstream and its tributaries dammed. Because of the main river displacement and tributary valleys partly flooded, dammed lakes develop as we can see in the Bolshoy Anyuy river valley in Chukotka (the Northeast of Russia) [18]. They may be considerably deep (up to tens of meters), depending on the initial topographic dissection and the lava thickness. For example, dammed lakes 50–70 m deep existed in the lower parts of the Maly Yenisey tributaries (Eastern Sayan mountains, Russia—see **Figure 1**). Sedimentary sequences, including lava series, studied in the Maly Yenisey valley, provided evidence of dammed lakes having been common enough in the main valley and its tributaries; the subaqueous outflow of lava resulted in pillow lava and hyaloclastite formation [16].

The lakes of the Jom-Bolok drainage basin (the largest of them—Khara-Nur—is approximately 9 km^2 in area) are drained under the lava at present (**Figure 4**) [25, 26]. In case such drainage is impossible, or it is less than the volume of water entering the lake, there may be several scenarios of further events. For example, the dammed lake may overflow into an adjacent valley, or even into another drainage basin [27].

Figure 4.
Jom-Bolok lava flow (light gray), volcanoes (red), and dammed lakes (blue): 1 - existing lake Khara-Nur, 2 - drained paleolake Zun-Ukhergei. White dotted line—Watershed between the Oka and the Bolshoy Yenisey rivers basins (Eastern Sayan mountains, Russia—See ***Figure 1****, No 9).*

Figure 5.
*Destroyed lava dams: A - the Hvita river, Iceland (2014); b - the Oka river, Eastern Sayan mountains, Russia (****Figure 1****, No 9). White arrow—The place of destroyed dam (2019, UVA photo courtesy by V. Pellinen).*

A similar situation periodically occurs in the upper reaches of the Jom-Bolok river, where the Khara-Nur Lake flows into the neighboring Bolshoy Yenisey river basin during periods of increased moisture. Examples of such river network restructuring are described also in Ref. [28] for the Sikhote-Alin' and the East Manchurian mountains (Russia-see **Figure 1**).

The lava dam may be also eroded completely or partly by the stream [27, 29, 30]. The remains of lava dams and traces of drained reservoirs have been preserved in the valleys of the river Oka, Dzhida, and many others. Jom-Bolok lava flow dammed Oka river with Zun-Ukhergei paleo-lake formation (**Figure 5**). In any case, an active erosion (downcutting) would initiate a mud- or debris flow descent in due course in the valley.

Explosive eruptions are more diversified in their consequences. Practically each of them is accompanied by an ejection of considerable volumes of *pyroclasts*. The ejecta volume at colossal explosive eruptions (VEI-6) exceeds 10 km^3 and may be more than 1000 km^3 during mega-colossal ones (VEI-8); the latter are relatively rare (about once in 50 thousand years). They usually result in development of ignimbrite mantles covering the pre-eruption surface and forming plains over an area of hundreds and thousands of square kilometers. More common are relatively small eruptions, though they also can produce practically instantaneous changes in local topography. During the Shtyubel cone (Ksudach caldera, Kamchatka, Russia) eruption in 1907, for example, the volume of ejected pyroclastics is estimated at 1.5 to 2 km^3; the tephra thickness varied from 0.5 to 3 m (**Figure 6a**) both in the immediate vicinity of the eruption center in the Ksudach caldera and at a distance of a few tens of kilometers from it (in the direction the wind was blowing during the eruption) [31].

In the late 1950s, Bezymyanny volcano (Kamchatka, Russia) ejected as much as 3 km^3 of tephra; the deposits formed a cover up to 40 m thick over an area of 70 km^2 and as thick as 40 cm over almost 500 km^2 [32, 33]. In explosions, blocks weighing as much as a few tons may be ejected as far as up to 300 m from the vent of ejection, those weighing a few kilograms—over a distance of 3–6 km [2], and the smaller-size ones may be thrown as far as 20 km [34]. The ash layer more than 30–40 cm thick would cause drying up or loss of vegetation [35], that is, in turn, has an effect on the erosion and slope processes [36, 37]. Ashfalls introduce noticeable changes into the local topography, reducing slope steepness and changing soil characteristics. The pyroclastic layers deposited over river valleys and watersheds may result in essential changes in the valley network pattern, as the new erosional landforms would develop in accordance with the new relief (**Figure 6b**) and may disagree with former valleys.

The *pyroclasts* ejected during an eruption are noted for high porosity and, consequently, for lightness, so that the material may be easily transported by wind and water and *concentrates gradually* in topographic lows (primarily *in river valleys*). Abundant rainfall or snow melting bring about the descent of mudflows (with solid ingredient proportion of more than 60%) or hyper-concentrated flows, with proportion of solid ingredient between 20 and 60%, which gradually transport pyroclastic material downstream (**Figure 6c**). That is best illustrated by a concrete example of Bezymyanny volcano (Kamchatka, Russia) eruption on March 30, 1956: the ejected pyroclastic induced an active snow melt that resulted in mudflows up to 75–85 km long formed in the Sukhaya Khapitsa valley on slope of the Klyuchevskoy volcano (Kamchatka, Russia) [38].

Lahar deposits are usually accumulated at the base of the volcano slopes; the length of the flows may be considerable, up to 185 km (Kelud volcano, Indonesia, 1919) and even as great as 300 km (Cotopaxi volcano, Ecuador, 1877). Traces of lahars have been recorded on most of the active volcanoes of the world having typically the explosive type of eruptions (**Figure 7a**): to take a few examples, there are 22 events of that kind recorded on Cotopaxi slopes in sixteenth-nineteenth centuries [39]; 20 glacial-volcanic

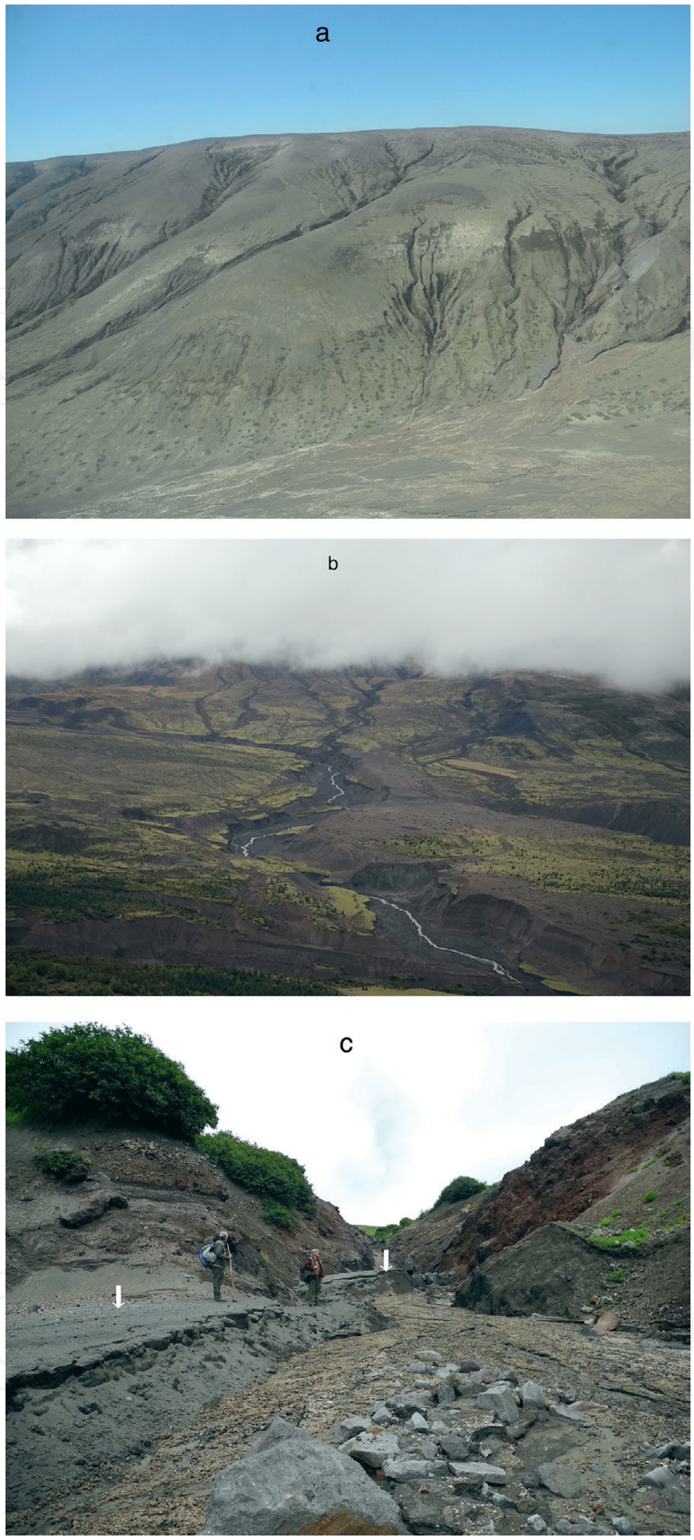

Figure 6.
Water redeposition of pyroclastic material: A - slopes with gullies in pyroclastic cover (Ksudach caldera, Kamchatka, Russia, 2016—See ***Figure 1****, No 12).); b - St. Helens volcano slopes with newly formed valleys in pyroclastic flow deposits (USA, 2018—See* ***Figure 1****, No 14); and c - modern lahars deposits in the Lagernyi creek valley (Ksudach caldera, Kamchatka, Russia, 2016).*

mudflows are known to occur on the Klyuchevskoy slopes (Kamchatka) in 1737 to 2008 time interval; there are 11 stages of large mudflows composed of melted snow and volcanic materials, which descend by the valleys on Shiveluch volcano (Kamchatka, Russia) southern slopes (the Kabeku, Bekesh, Baydarnaya, Kamenskaya, and other rivers) from 1854 to 2009 (**Figure 7b**) [11]. An eruption of the small Chaiten volcano (Chile) in 2008–2009 was responsible for three lahars; one of them (May 2009) inflicted damage on the city of Chaiten (**Figure 3**). Observations performed in valleys around volcanoes [2] proved that the valley bottom may be hazardous for a considerable length of time (several decades) after the eruption because of a lot of the unconsolidated sediments within and the expected subsequent lahar events in the valleys.

Quite often explosions occur not only with the ejection of pyroclasts but also with partial demolition of the volcanic cone. Even in the case of a small-size volcano, when its top is blown off, large blocks are scattered, and adjoining valleys may be dammed with coarse material. That often results in a dammed lake formation or in rising of the preexisting lake level. Such a case was recorded, for example, in 1907 in the uppermost reaches of the Teplaya river (Ksudach caldera, Kamchatka, Russia). Later, when the dam is broken (**Figure 8**), a mudflow descent occurs inevitably, which is confirmed by the presence of a large fan at the river mouth. Intracaldera lake breakout floods have been identified in the Taupo volcanic zone (New Zealand) also [40].

One-sided destruction of the volcanic cone during eruption—the so-called directed blast (or more neutral term - sector collapse)—is often accompanied by a debris avalanche development (see **Table 1**). As a result, non-sorted debris is deposited on the part of slope the explosion had been directed at. As noted by Ref. [34], the rock fragments may be thrown off over a distance of 29–30 km. A large debris avalanche goes as far as 85 km from the cone failure and covers an area of 100 to 1000 km^2 [2]. The resurgent material may either infill river valleys completely over a considerable length or build up dams there. The case of a valley infilling was recorded during the Bezymyanny volcano eruption (Kamchatka, Russia) in 1956 when valleys on the eastern slope of the mountain were filled with debris and ejecta over a length of a few kilometers [32]. When streams resumed their activity, a series of copious mudflows developed and brought the material onto the right side of the Kamchatka river valley [38]. Debris avalanches in the Chakachatna river valley (Alaska, USA) resulted in the formation of long dams and dammed lakes with depth up to 150 m [14]. Not-so-huge lakes were formed in valleys around St. Helens volcano after 1980 eruption (**Figure 9a**). The avalanches descent during the Holocene Shiveluch volcano eruptions (Kamchatka, Russia) brought about a radical restructuring of the valley network: the Kabeku river captured a parallel water stream blocked with large blocks of the avalanche (**Figure 9b**) [41].

Figure 7.
*Lahars: A - on the Fuego volcano slope (Guatemala, 2013—See **Figure 1**, No 34); b - in the Kabeku river valley (Shiveluch volcano foot, Kamchatka, Russia, 2013—See **Figure 1**, No 13).*

Figure 8.
A fragment of a destroyed debris dam (white arrow) at the source of the Teplaya river cause a rise in the level of Ksudach caldera's lakes by 15 m (white dotted line) after the eruption of 1907. The black dotted line shows the top of the Shtyubel cone destroyed by the 1907 explosion (Kamchatka, Russia, 2016—See ***Figure 1****, No 12).*

Figure 9.
Debris avalanches impact: A - dammed Coldwater lake in the Coldwater Creek valley with hummocky relief remnants (white arrow) as islands (St. Helens volcano, USA, 2018—See ***Figure 1****, No 14); b - a debris avalanche deposits with soil-pyroclastic cover in Kabeku river valley (Shiveluch volcano, Kamchatka, Russia, 2013—See* ***Figure 1****, No 13).*

In explosive eruptions, a heavier part of the eruptive column may form pyroclastic flows—a mixture of burning hot (often above 600–700°C) blocks, ash, and volcanic gases. They descend from the eruptive vent downslope at a rate of 100 m/s or more [2] mostly following valleys of streams dissecting the slopes. There are known occasions when pyroclastic flows rose upstream valleys passing over the mountain ranges enclosing caldera; such a case was reconstructed [42] to have occurred during the latest caldera-forming eruption of Ksudach volcano (Kamchatka, Russia) 1725 yr. BP (**Figure 10a**). As a result, the valleys turn out to be filled with pyroclasts; later the loose pyroclastic mantle was eroded, and mudflows arose. The pyroclastic flows affect great areas, up to ten and hundreds of square kilometers. After Shiveluch volcano eruption (Kamchatka, Russia) in 1964, the affected area was 45.5 km^2 [43]. In the succeeding years, the flows repeatedly descended by the stream valleys of the southern slope, and their length varied between 8 and 28 km [44]. Pyroclastic flows are known, however, to be as long as 100 km [1, 34].

On entering a valley, a pyroclastic flow covers its floor completely and, in common with lava flows, forms a convex transversal profile. On the Shiveluch volcano, the pyroclastic flow deposits (**Figure 10b**) vary between 2 and 5 m and 40 and 50 m [43–45]. The deposits may be loose or welded (as pumice and ignimbrites). Accordingly, the former is more easily destroyed by erosion and mudflow formation. Pumice and ignimbrite flow during *caldera collapse* often form plains over pre-existing landforms. However, they are seldom marked by considerable durability and their surface is often dissected by erosion to a stage of badland (**Figure 10c**).

In common with lava flows, the pyroclastic ones may block the tributaries at their entering the main valley and form dammed lakes (**Figure 11a**). The pyroclastic dams, however, are not very strong and may be broken by erosion and mudflows within a few years after the eruption. Such was the case of the southern slope of Shiveluch volcano (Kamchatka, Russia) [45]. As the streams are usually overloaded with loose pyroclasts, the deposition rate in the lakes is rather high; to take but one example, a series of horizontally stratified sands more than 6–7 m thick accumulated in the dammed lake at the Sukhoy Bekesh river per 3 years (**Figure 11b**). The lakes dammed by ignimbrites are long-lived and large, and their depth may be as great as 100 m like in Tadamy river-dammed lake (Japan). But this ignimbrite dam also was destroyed with debris (mud) flow formation along a river valley 150 km long [46]. Similar situations with ignimbrite dams were also reconstructed by [40] for Tarawera lake in Taupo volcanic zone (New Zealand).

During the observation period of the Shiveluch volcano activities (1964–2013), the lahar descent was always preceded by the pyroclastic flow eruption. This fact led I.B. Seinova and her colleagues [47] to the conclusion that the pyroclastic flows is a trigger mechanism in the lahar initiation. In 2009, the eruption of Sarychev peak volcano (Matua Isl., the Kuriles, Russia—see **Figure 1**, No 36) produced eight pyroclastic flows, which subsequently gave rise to seven mudflows (lahars) [48]. A regular lahar formation has been recorded after Merapi volcano (Indonesia) eruptions usually accompanied by pyroclastic flows. Ten out of 18 largest streams originated on the volcano became repeatedly the ways of lahar descent [5]. The studies of the pyroclastic flow deposits on St. Helens volcano showed that the pyroclastic flows (or pyroclastic density currents–PDC) exert a noticeable erosive effect on the substrate [49], particularly in case they move downward by linear hollows on steep volcanic slopes. Avulsions, riverbank erosion, and riverbed downcutting were presented as lahars geomorphic impacts at Merapi volcano river valleys after the 2010 explosion [5, 50].

After a large eruption accompanied by pyroclastic ejection, the solid runoff of rivers in volcanic regions may be several orders of magnitude greater than before the eruption, that is distinctly seen in the graphs constructed for Kamchatka and Tolbachik rivers (Kamchatka, Russia) [51]. According to Ref. [2], after St. Helens eruption in 1980, the annual solid runoff of rivers in the vicinities increased by a factor of 500, and even 20 years after the event the annual suspended load increased ~100 times as compared with the value before the eruption. The streams flowing from volcanoes are usually overloaded with rock debris varying in size, and great volumes of pyroclasts (including that redeposited by lahars) are to be transported by the rivers [52].

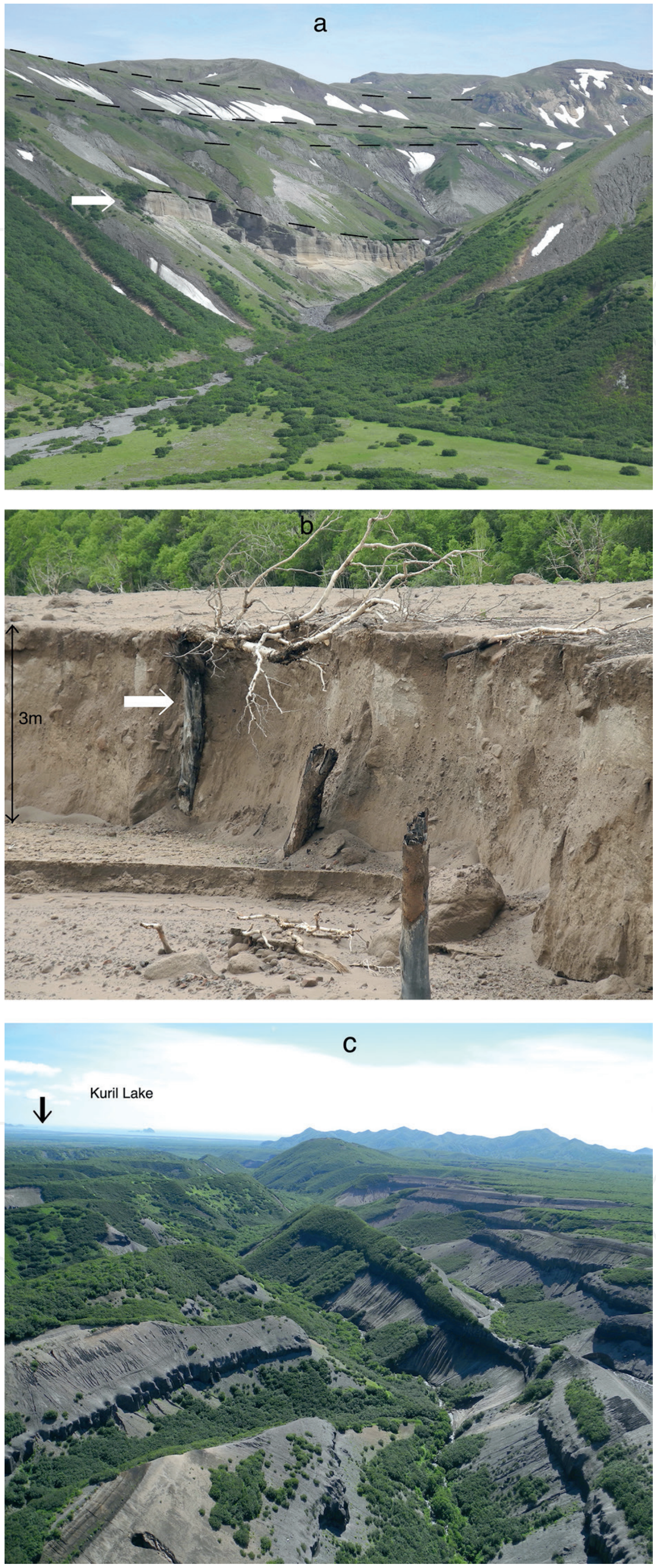

Figure 10.
*Pyroclastic flow (PF) deposits: A - traces PFs (black dotted lines) expand upstream (upslope) passing over the mountain ranges enclosing Ksudach caldera (2016); b - burnt birch trunks in a pyroclastic flow in Kabeku river valley, Shiveluch volcano (2013); and c - dissected Holocene pyroclastic plain near Kuril lake caldera (2016); all photos—Kamchatka, Russia (see **Figure 1**, No 12, 13, 20).*

Figure 11.
*Dammed lake between two pyroclastic flows (a - the Kabeku river valley) and destroyed dammed lake deposits (b - the Bekesh river valley), Shiveluch volcano slopes, Kamchatka, Russia (2013—See **Figure 1**, No 13).*

Observations in the valleys of the Kabeku and Bekesh rivers (the Shiveluch volcano slopes, Kamchatka, Russia) allow us to conclude that the frequent descent of lahars causes many changes not only in the nature of the runoff but also in the morphology of the valleys in the areas of their deposition.

In case the eruption occurs in a lake (within caldera or in a dammed water body in a valley), or in its immediate vicinity, no matter if it is underwater or above, it results in the water expulsion from the lake and a mudflow descent from the slopes or along the valley. According to Refs. [6, 7, 9, 12, 40], the generation of eruption-triggered lahars by the ejection of water from lakes is widespread in New Zealand and in other regions of the world. Since 1861 a lot of lahars have been generated from the Crater lake on Ruapehu volcano. The evidence of such phenomena is traceable in the Teplaya river valley (Ksudach caldera, Kamchatka, Russia) and in valleys of other rivers flowing out of volcanic lakes [53]. A subaqueous explosive eruption was observed in 1996 in Karymsky lake (the Akademia Nauk caldera, Kamchatka) with a series of tsunami to 15 m high and breakthrough floods from lake along Karymskaya river valley [54]. Then, at the source of the river, a dam of pyroclastic material arose, which after a few months was broken through with the descent of the lahar.

In the regions of the continental ice sheet, the eruption taking place under a thick ice cover may create giant outburst floods of meltwater known under the name of *jökulhlaup*. At present, they are known to occur in Iceland [55, 56]; during the Quaternary cold intervals, they seem to have happened in Kamchatka [57], as well as on the east Tuvinian lava upland (Eastern Sayan mountains, Russia—see **Figure 1**) [58] and in other volcanic regions of midlatitudes. When an eruption takes place under glacier, the meltwater forms a subglacial water body under considerable pressure; subsequently, the ice may subside and an outburst flood occurs accompanied by the abrupt release of great volumes of water, ice fragments, and stone debris being transported over a large distance, particularly along river valleys. Enormous volumes of water involved in the process account for the great scale of the phenomenon. For example, the length of the flows, their rate, and the transported material volume exceed the characteristics of lahars by orders of the value. For example, the Katla volcano eruption under Myrdalsjökull glacier in 1918 induced a jökulhlaup of 8 km^3 volume and a flooded area of 600–800 km^2. Those flows maybe 20 to 70 m deep and 8–9 km wide. No river channel can hold a great volume of water. Quite often, the passage of the flood causes changes in topography and a large-scale restructuring of river network. That may be illustrated by a case of a subglacial eruption of Grimsvötn volcano in 1861 when the Skeidara river channel was displaced westward by 13 km [56, 59, 60].

Quite often volcanic eruptions are accompanied by *volcanic-tectonic manifestations*, such as appearance of *fissures* and *deformations of the land surface* (uplift or subsidence of the land surface by a few meters); less common are *collapse calderas*. We mentioned above that during the formation of calderas, not only the river valleys are filled with pyroclasts, but also the formation of flat areas around the calderas, where pyroclastic flows overlap the original relief (**Figure 12**). The abundance of pyroclastic material favors the descent of lahars along the newly formed river network (see **Figure 10**); however, the influence of caldera formation on valleys is not limited to this.

The changes in topography may lead to deformations of valleys' long profiles, to displacement or restructuring of the river network. Earlier we described such changes observed in the Ksudach caldera complex (Kamchatka, Russia); among them are reconfigurations of the valleys' lowermost reaches after the caldera collapse in 1725 (the date is given after [61]), and the stream network restructuring induced by Shtyubel cone growth [29, 30]. The changes in the river network structure accompanying volcanic activities or resulting from them are also catastrophes of various scales; they are often accompanied by outbursts or spillover of dammed lakes and the subsequent descent of mudflows. So, the growth of the Shtyubel cone led to a change in the longitudinal profile of the Lagernyi creek with the formation of a lake, when overflowing and discharging water, a mudflow was formed.

The rapid extrusion growth can also provoke catastrophic processes in the valleys. So, about 1600 years ago [41] because of the giant blocks collapse of the actively grown extrusion Dikiy Greben' (Kuril Lake caldera, Kamchatka, Russia),

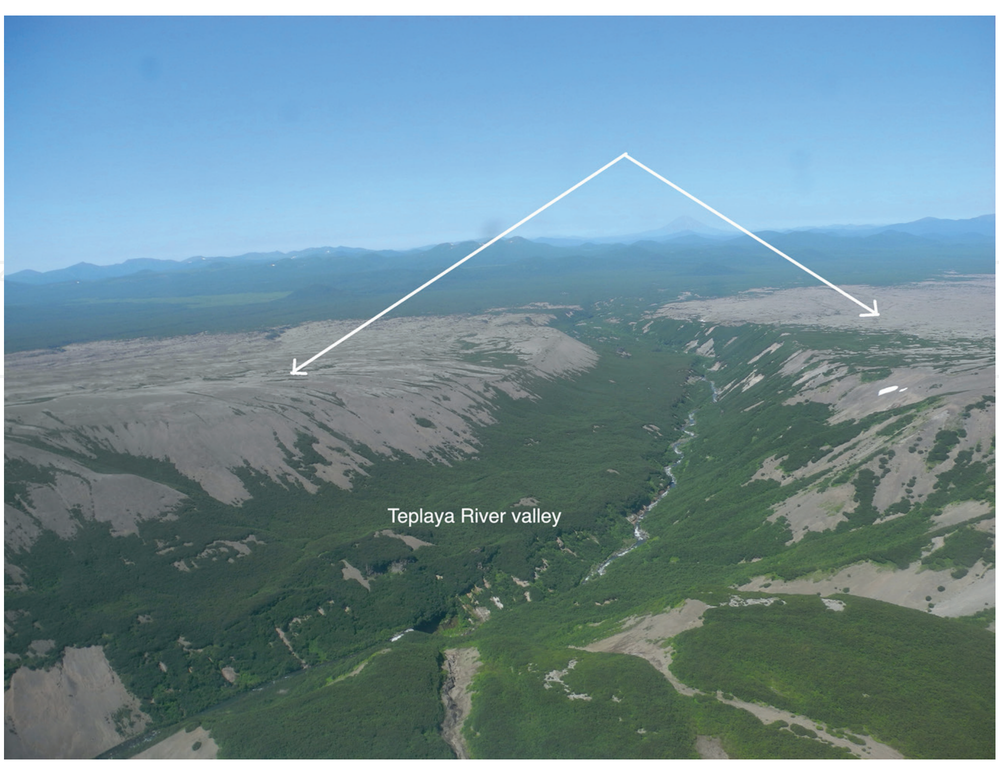

Figure 12.
*The fragments of the pyroclastic plain around Ksudach caldera (white arrows) with Teplaya river valley (Kamchatka, Russia, 2016—See **Figure 1,** No 12).*

the Ozernaya river valley flowing from the Kuril lake was blocked (**Figure 13**). Lavas large blocks can be traced on the left side of the valley and in the riverbed in its upper reaches. The wreckage is characterized by numerous cracks that arose because of their

Figure 13.
*Dikyi Greben' extrusion (a - black arrow) and giant blocks (white dotted lines)—Traces of it collapse; b - destroyed dam (white dash line) in the Ozernaya river valley (Kuril Lake caldera, Kamchatka, Russia, 2020—See **Figure 1**, No 20).*

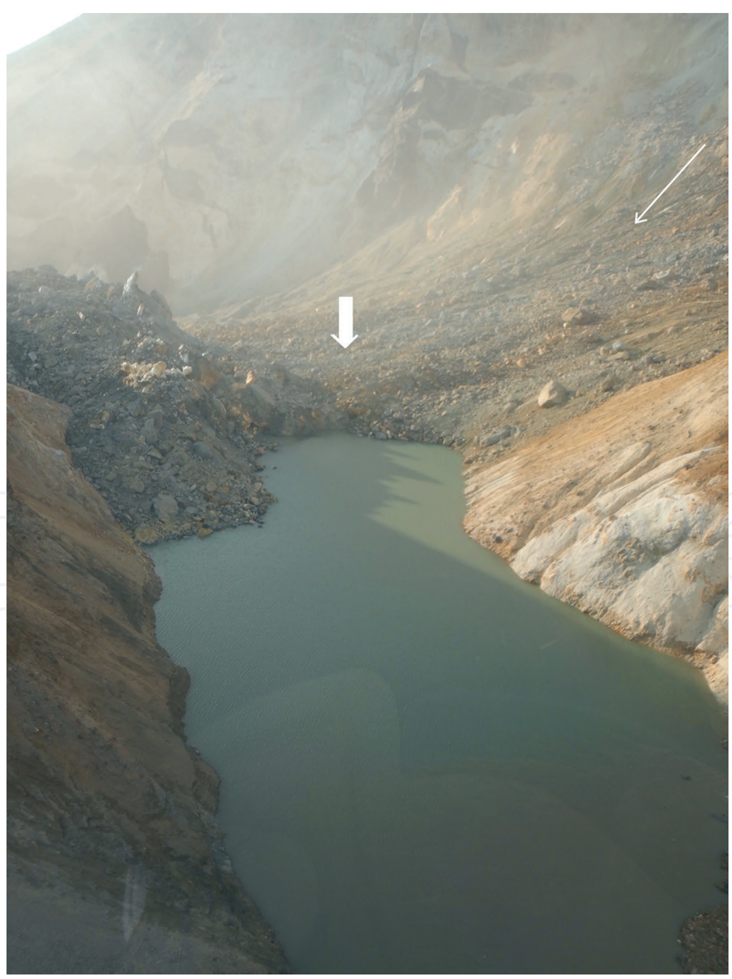

Figure 14.
*New dammed lake in the Vulkannaya river upper reaches after the collapse of the Mutnovsky volcano crater wall: Thin white arrow—Direction of rock fragments displacement, thick arrow—The new dam (Kamchatka, Russia, 2021—See **Figure 1**, No 21).*

fall at more than 2 km. According to our estimates, the dam height reached 20 m and its destruction was inevitably accompanied by a debris flow.

Among the factors contributing to the hazardous processes in river valleys are the presence of unstable rocks (fissured, loose, or altered by hydrothermal processes), seismic shocks (even weak), or extremely heavy rainfall. There are well-known facts of debris avalanches, rockfalls, and other kinds of active mass wasting not only during the eruptions (as in the case of Shiveluch and St. Helens), but also long after them (as on volcanoes Parinacota in Chile, Shasta in California, Casita in Nicaragua, and others) [2]. Obviously, seismic events, both accompanying volcanism and directly independent of it, can cause the destruction of *the crater lake walls* or the body of a volcanic dam of various origins [53, 62]. In any case, these will lead to lake outbursts and mudflow descent. On the other hand, if an earthquake triggers a landslide, a new dammed lake may appear in the valley. In August 2021, we observed the consequences of a collapse on the northern wall of the crater of the Mutnovsky volcano (Kamchatka), where 19.08 another dammed lake appeared and mudflow descended (**Figure 14**).

Large-scale geomorphic catastrophes may occur in valleys within the zones of hydrothermal activities. In those zones, rocks in the valley sides are densely fissured, essentially altered, and often turned into clay by the chemical weathering processes and water encroaching. The rocks' hydrothermal weathering and moistening processes stimulate a wide range of slope processes—rockfalls, landslides, slumps, flow slides. The hydrothermal clays distribution and the presence of the steam and thermal water outlets on the valley slopes favor the numerous displacements, resulting in the formation of the local multilevel landslide and block-slide terraces. In some cases, several tiers of similar terraces can be observed (**Figure 15**).

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 because 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 along the valley. The further slope and alluvial material transportation and redeposition occur mainly due to the debris flows, which are formed either directly during the gravity collapse, or during the dams' destruction and the descent of temporarily dammed reservoirs. This is well confirmed by the observations carried out in the

Figure 15.
*Landslide terraces (white arrows and dashed lines): A - on the Geysernaya river valley sides (Uzon-Geysernaya caldera, Kamchatka, Russia—See **Figure 1**, No 25), periodically blocking the river with subsequent debris flows originating (2013), b - in Kislyi Creek, Mendeleev volcano, Kunashir Isl. (Russia, 2018 - see **Figure 1**, No 3).*

Figure 16.
The Geyzernaya river valley (Uzon-Geysernaya caldera, Kamchatka, Russia, 2021—See ***Figure 1,*** *No 25): A - partly destroyed dam 2007 (1) with drained lake (2), b - dam 2014 (white arrow). Black arrows—River flow direction, white dashed lines—Dam borders.*

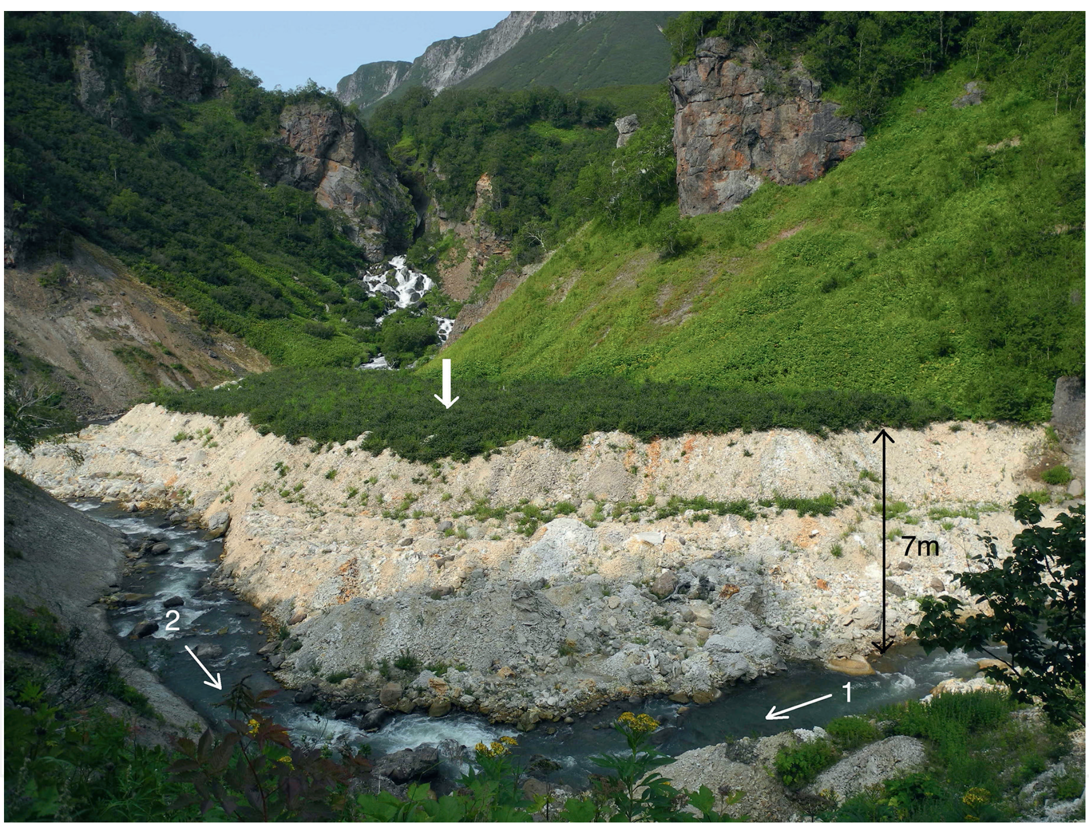

Figure 17.
The debris flow deposits formed the accumulative terrace (white arrow) in the Geysernaya river mouth (Uzon-Geysernaya caldera, Kamchatka, Russia, 2021—See ***Figure 1****, No 25): 1 - Geysernaya river, 2 - Shumnaya river.*

Geysernaya river valley (Uzon-Geysernaya caldera, Kamchatka, Russia) [63–67], where currently there are two similar dams—one (2007) is already cut by the river, and the other (2014) is in the early stages of erosion (**Figure 16**).

The debris flow deposits form the accumulative terraces (**Figure 17**); in the valleys of some watercourses, the debris flow 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 [68], 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 for other watercourses of the high hydrothermal activity territories in the Kuril-Kamchatka region [69, 70].

3. Conclusion

River valleys in volcanic regions become occasionally zones of rapid deposition of juvenile and resurgent material. The latter comes from volcanic eruptions of effusive or explosive type, volcanic-tectonic or hydrothermal processes (lava outflow, pyroclast ejection, volcanic cone breakdown, or explosion, sliding of rock mass weakened because of hydrothermal activity). That results in the river valleys being filled with volcanic material diversified in composition and properties, with the deposition proceeding from the upper links of the river network downstream. At the same time, the valleys serve as routes of active, and mostly intermittent (steplike), displacement of the material by various agents. Most often it takes place as a result of volcanic mudflow descent immediately after eruption due to ice or snow melting or resulting from abundant rainfalls. In some cases, however, a series of 2–3 catastrophic events occurring in a valley ends with a mudflow descent; the mudflows may occur repeatedly and are known as secondary lahars. As follows from long-term observations, the series of such events may continue through a few decades, or even centuries [2].

When considering geomorphic hazards controlled by volcanic activities, we recognized a lot of kinds of event chains of that type. An analysis of the chains permitted to identify the main geomorphic factors responsible for catastrophic events in river valleys are as follows: quick depositions of volcanic products; displacement of loose rock masses; slope angle changes; and accelerated erosion. Mudflows moving loose material downstream "in the pulse mode" occur when the loose deposits brought into valleys are actively eroded by the streams arising not only from abundant rainfall, or snow and ice melting but also resulting from an abrupt release of water from dammed lakes in case of the dam breakthrough. We agree with S. Chernomorets and I. Seinova [11] in that the mudflows are "usually the final stage in the chain of catastrophic events in the course of eruptions" (p. 57). There are also many other exogenic—fluvial, eolian, cryogenic processes taking part in the processing and transportation of the volcanic deposits, but it is much rarer that they assume the form of catastrophes [45].

It may be concluded from the above that the rivers in volcanic areas are particularly vulnerable and endangered because of several factors: large volumes of the material supplied and transported; high rates of endo- and exogenic processes on the adjoining territories; and highly energetic activity of the streams themselves, which induces a wide assortment of hazardous events and exerts a notable effect on the relief-forming processes.

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