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RESEARCH ARTICLE

Dendrogeomorphic reconstruction of lahar activity and triggers: Shiveluch volcano, Kamchatka Peninsula, Russia

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Abstract Lahars are highly concentrated, water-saturated volcanic hyperconcentrated flows or debris flows containing pyroclastic material and are a characteristic mass movement process on volcanic slopes. On Kamchatka Peninsula (Russian Federation), lahars are widespread and may affect remote settlements. Historical records of past lahar occurrences are generally sparse and mostly limited to events which damaged infrastructure on the slopes or at the foot of volcanoes. In this study, we present a tree-ring-based reconstruction of spatiotemporal patterns of past lahar activity at Shiveluch volcano. Using increment cores and cross sections from 126 *Larix cajanderi* trees, we document 34 events covering the period AD 1729–2012. Analyses of the seasonality of damage in trees reveal that 95% of all lahars occurred between October and May and thus point to the predominant role of the sudden melt of the snow cover by volcanic material. These observations suggest that most lahars were likely syn-eruptive and that lahar activity is largely restricted to periods of volcanic activity. By contrast, rainfall events do not seem to play a significant role in lahar triggering.

Keywords Dendrogeomorphology · Lahars · Shiveluch volcano · Tree rings · *Larix cajanderi*

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Introduction

Kamchatka Peninsula is located in the Russian Far East and is one of the most active volcanic regions along the Pacific Ring of Fire. The region comprises 300 volcanoes, around 30 of which are presently active (Solomina et al. 2008). Volcanism in the easternmost region of the Russian Federation presumably started with the formation of a first generation of stratovolcanoes some 50–60 kyr ago (Ponomareva et al. 2007b). It persisted over the course of the Pleistocene and the Holocene as a result of the subduction of the Pacific tectonic plate under Kamchatka Peninsula (Ponomareva et al. 2007b). Current measurements indicate that the greatest contemporary subduction velocities of the Pacific plate occur below the volcanic complex of the Klyuchevskoy volcano group and Ostryj Tolbachik volcano in the northern part of Kamchatka with subduction rates of ca. 8 cm year^{-1} (Adveiko et al. 2007; Ponomareva et al. 2007b).

A wealth of records exists on volcanic eruptions of the recent past, pointing to significant activity of at least 37 large volcanoes during the late Pleistocene and Holocene, whereas 18 volcanoes contain evidence of major changes in shape due to single or multiple sector collapses resulting in huge debris avalanches, lahars, and/or the deposition of thick volcaniclastic deposits (Belousov et al. 1999; Ponomareva

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et al. 2006). The reconstruction of these and other events during the Holocene has been based mainly on geological mapping, local geological and petrological studies (e.g., Gorbach et al. 2011, 2013; Dirksen et al. 2006), tephrochronological studies (Braitseva et al. 1997; Ponomareva et al. 1998; Dirksen et al. 2011), as well as radiocarbon dating (Braitseva and Melekestsev 1990; Braitseva et al. 1993; Ponomareva et al. 1998, 2007b).

In addition, starting from the 1990s, the Kamchatka Volcanic Eruption Response Team (KVERT; http://www.kscnet.ru/ivs/kvert/index_eng.php), Far East Division of the Russian Academy of Sciences, has started to monitor volcanic activity of Kamchatkan volcanoes systematically and therefore ensures a continuous observation of volcanic eruption and other syn-eruptive processes such as lahars. Since 2002, the activity of Shiveluch volcano is observed daily by continuously recording webcams.

Shiveluch volcano is located in the northeastern part of Kamchatka Peninsula (N 56° 38′, E 161° 19′; Fig. 1). With a magma discharge of 3.6×10^7 t year^{-1} (Melekestsev et al. 1991), it is one of the most active and prolific volcanoes on the peninsula (Ponomareva et al. 2007a; Girina and Nuzhdaev 2014). The structure of the edifice is complex, consisting of a young eruptive center in its eastern part (Young Shiveluch, 2800 m a.s.l.), active throughout the Holocene, and an older extinct stratovolcano (Old Shiveluch, 3283 m a.s.l.), active during the Late Pleistocene and with evidence of multiple flank collapses (Ponomareva et al. 2006; Gorbach et al. 2013).

Shiveluch volcano produced at least 60 (primarily Plinian) eruptions during the Holocene, resulting in the deposition of thick layers of pumiceous ignimbrite, tephra fall, debris avalanche, and lahar deposits. Peaks in volcanic activity occurred between 8500 and 6400 BC, 2600–1700 BC, and from 900 BC to the present (Ponomareva et al. 2007a). However, even if the recent eruptional events that occurred at Shiveluch volcano are known, detailed information about environmental hazards related to volcanism (i.e., lava flows, landslides caused by slope collapses, and/or lahars) is scarce. During the Holocene, the major disasters provoked by Shiveluch volcano were through the occurrence of tephra falls and lahars (Ponomareva et al. 2007b). Due to scarce information from historical archives (covering only the last 300 years; Ponomareva et al. 2007b, Solomina et al. 2008) and imprecise observations, the lahar chronologies in this region are incomplete.

In Kamchatka, records of lahars—saturated, highly concentrated, and very rapid volcanic flows containing volcanic fragments, pyroclastic material, water, and rock debris—are

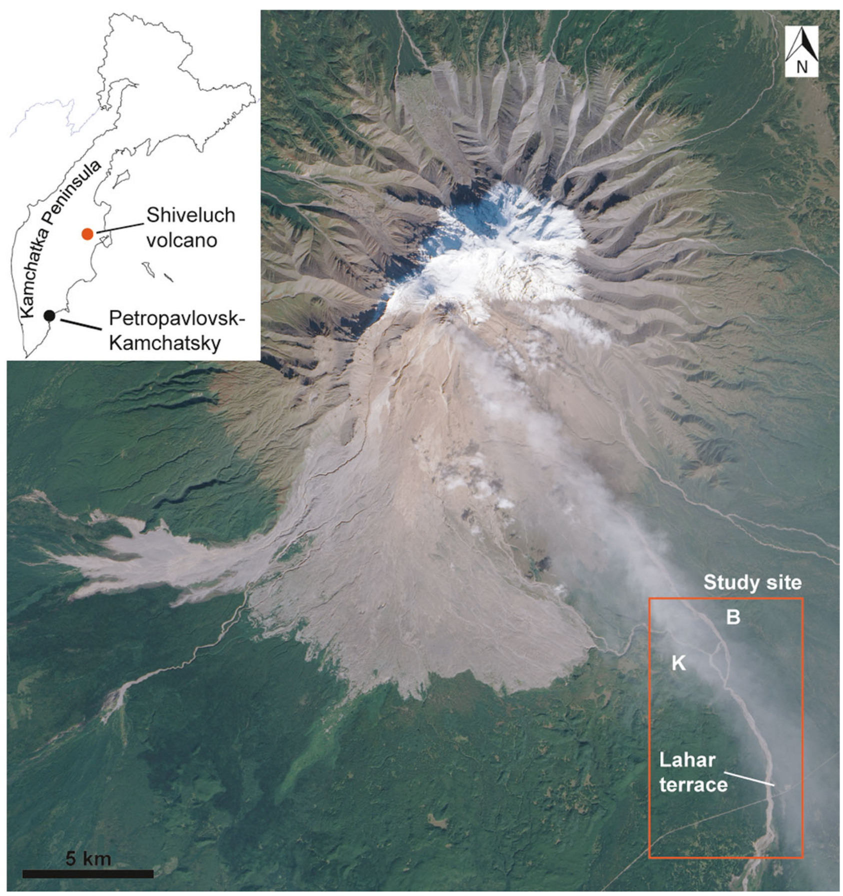


Fig. 1 The study area is located SE of Shiveluch volcano (N 56° 38′, E 161° 19′) in the northeastern part of the Kamchatka Peninsula, Russia. The present dendrogeomorphic study was carried out above, at, and below the confluence of Bekesh (B) and Kabeku (K) lahar channels. Satellite image from NASA Earth Observatory, captured on 7 September 2010. http://eoimages.gsfc.nasa.gov/images/imagerecords/45000/45872/shiveluch_ali_2010250_lrg.jpg

generally very scarce, and archival records are typically limited to events related to historic volcanic eruptions (Ponomareva et al. 2007b).

The record of lahars in the region is thus clearly biased towards a very limited number of recent, destructive events, as well as to extreme, yet typically old, events of the Holocene found in geological outcrops. A more systematic record of recent (i.e., latest Holocene) lahars does not therefore exist for the region, and continuous monitoring of volcanic activity and related phenomena usually covers the past 20 years at best.

In areas with old-growth forest stands, the temporal frequency and spatial patterns of past geomorphic processes can be dated with growth ring records of trees that have been impacted by events during their lifetime. The approach is called dendrogeomorphology (Alestalo 1971; Stoffel et al. 2010) and has been demonstrated repeatedly to be a very precise and reliable means of spatiotemporal process reconstruction (Stoffel and Bollschweiler 2008; Stoffel et al. 2013; Stoffel and Corona 2014). Some examples of dendrogeomorphic research focused primarily on the reconstruction of rockfall (Stoffel et al. 2005a; Corona et al. 2013a; Trappmann et al. 2013, 2014; Trappmann and Stoffel 2015; Morel et al. 2015), landslide (Lopez Saez et al. 2012; Šilhán et al. 2012, 2015), (flash) floods (Ballesteros et al. 2010a,b; Ruiz-Villanueva et al. 2010; Ballesteros-Cánovas et al. 2015a, b), debris flow (Bollschweiler et al. 2007; Procter et al. 2011, 2012; Šilhán et al. 2015), and snow avalanche (Corona et al. 2010, 2012, 2013b; Schläppy et al. 2014, 2016) histories. To the present day, lahars have been analyzed much less often with dendrogeomorphic techniques (Bollschweiler et al. 2010; Franco-Ramos et al. 2013, 2016).

In one of the first published papers working on volcanic mass movements, Hupp (1984) applied tree-ring records to provide a 300-year record of debris flow frequency at Mount Sashta in the Cascade Range, California. Many of these debris flows were indeed cold lahars. Pierson (2007) used trees establishing on lahar deposits to obtain minimum ages of young geomorphic surfaces formed after destructive events. In a rather comparable approach, a selected number of past lahars on Shiveluch volcano have been constrained through the analysis of kill dates of trees and the dating of wooden material in lahar deposits (Solomina et al. 2008). More recently, research has been, however, expanded to include direct evidence of tree damage inflicted by lahars into dendrogeomorphic studies, such that a direct dating of past events has become possible with at least annual and sometimes even monthly resolution (Stoffel et al. 2005a,b; Bollschweiler et al. 2007; Stoffel 2008). This new generation of studies on volcanic eruptions and related hazards focused primarily on recent lahar histories of Popocatépetl (Bollschweiler et al. 2010) and Colima volcanoes (Franco-Ramos et al. 2013) in the Mexican Volcanic Belt for which the activity of twentieth century flows could be reconstructed.

To improve lahar risk assessments, an improved understanding of temporal and spatial patterns as well as triggers of volcanic hazards is critically needed. The aim of this study is to apply dendrogeomorphology to two active lahar channels on Shiveluch volcano (Bekesh and Kabeku) so as to (i) reconstruct the temporal activity of lahars in the channels, (ii) determine the spatial patterns and the minimum reach of reconstructed events, as well as to (iii) identify possible triggers, seasonality, and return period of past lahars.

Study site

Shiveluch volcano (N 56° 38′, E 161° 19′) is located in the Central Kamchatka Depression in the northeastern part of the Kamchatka Peninsula (Fig. 1). The summit of Old Shiveluch is composed of a series of andesitic and basaltic lava flows (Gorbach et al. 2013), which are well visible on the contemporary southern and eastern flanks. The composition of erupted material is mainly represented by medium-potassium, hornblende-rich andesites, which suggest the existence of a huge andesitic magma chamber under the volcano and magma generation above the mantle slab of the subducting Pacific plate (Ponomareva et al. 2007a).

Historical eruptions and lahars

At least 60 eruptions have been reconstructed over the course of the Holocene, resulting in the deposition of thick layers of pumiceous ignimbrite, tephra fall, debris avalanche, and lahar deposits.

First written records of volcanic activity (Table 1) date back to 1739 and report on eruptions in 1739, 1790, and between 1790 and 1810, but this information is uncertain (Gorshkov and Dubik 1970). Archival records become more precise after a large eruption occurred in 1854 (Gorshkov and Dubik 1970), when several lahars were triggered. In the aftermath of the large mid-nineteenth century eruption, Shiveluch was characterized by moderate but continuous volcanic activity until the 1960s (i.e., 1879–1883, 1897–1898, 1905, 1927–1929, 1944–1950; Gorshkov and Dubik 1970; Solomina et al. 2008; Chernomorets and Seynova 2010). A large Plinian eruption of Shiveluch volcano occurred on 12 November 1964, with sector collapses and a phreatic explosion which initiated lahars and debris avalanches with a total volume of about 2 km^3 and deposited 0.3 km^3 of fall deposits and 0.4 km^3 of ignimbrite around the volcano (Gorshkov and Dubik 1970; Ponomareva et al. 2007a). The 1964 deposits are still visible in the field and on satellite imagery (Fig. 1). Since 1980, a lava dome has been growing in the 1964 crater and has since resulted in occasional ash falls, block-and-ash flows, pumice flows, and related processes including landslides and lahars (Ponomareva et al. 2007a; Chernomorets and Seynova

Table 1 Historical eruptions of Shiveluch volcano

Eruption date	Dating methods	Uncertain or certain	VEI	Eruption type	Confirmed lahars	Affected rivers of Shiveluch catchment					References
						Baidarnaya	Kabeku	Mutny	Kamenskaya	Bekesh	
ca. 1021–1057	Tephrocronology and 14C	C									Solomina et al. (2008), Ponomareva et al. (1998), Braitseva et al. (1997), Gorshkov and Dubik (1970)
ca. 1430	Tephrocronology and 14C	C									Solomina et al. (2008), Ponomareva et al. (1998), Braitseva et al. (1997) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270) http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
ca. 1641–1663	Tephrocronology and 14C	C									Solomina et al. (2008), Ponomareva et al. (1998), Braitseva et al. (1997)
ca. 1700	Tephrocronology and 14C	U	3								Solomina et al. (2008), Ponomareva et al. (1998) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1739	Historical record	U	3								Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1790–1810	Historical record	U									Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1–2 March 1854	Historical record	C	5	Paroxysmal	1–2 March 1854	x	x	x			Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1879–1883	Historical record	C	3								Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1897–1898	Historical record	C	2								Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.).

Table 1 (continued)

Eruption date	Dating methods	Uncertain or certain	VEI	Eruption type	Confirmed lahars	Affected rivers of Shiveluch catchment					References
						Baidarnaya	Kabeku	Mutny	Kamenskaya	Bekesh	
											Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
1905	Historical record	C									Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270) http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
19(27)28–1929(3-0)	Historical record	C	1								Solomina et al. (2008), Gorshkov and Dubik (1970) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
November 1944–April 1950	Historical record	C	2								Solomina et al. (2008) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
12 November 1964	Historical record	C	4	Paroxysmal	12 November 1964	x	x		x		Solomina et al. (2008), Gorshkov and Dubik (1970), Belousov et al. (1999) Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
August 1980–December 1981	Historical record	C	1		1980–1981						Girina et al. (2016) Shevchenko et al. (2015)[a] Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270). http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
March–September 1984	Historical record	C	2		1984						Global Volcanism Program, 1984. Report on Sheveluch (Russia). In: McClelland, L (ed.), Scientific Event Alert Network Bulletin, 9:5. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.SEAN198405-300270
May–October 1985	Historical record	C	2								Volcanological Society of Japan, 1988, Bulletin of Volcanic Eruptions, no. 25 Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270)

Table 1 (continued)

Eruption date	Dating methods	Uncertain or certain	VEI	Eruption type	Confirmed lahars	Affected rivers of Shiveluch catchment					References
						Baidarnaya	Kabeku	Mutny	Kamenskaya	Bekesh	
											http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
March 1986–February 1988	Historical record	C	3		1986–1988						Global Volcanism Program, 1988. Report on Sheveluch (Russia). In: McClelland, L (ed.), Scientific Event Alert Network Bulletin, 13:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.SEAN198804-300270
December 1988	Historical record	C	2								Global Volcanism Program, 1988. Report on Sheveluch (Russia). In: McClelland, L (ed.), Scientific Event Alert Network Bulletin, 13:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.SEAN198804-300270
April–June 1989	Historical record	C	2		1989						Global Volcanism Program, 2013. Sheveluch (300270) in Volcanoes of the World, v. 4.5.1. Venzke, E (ed.). Smithsonian Institution. Downloaded 09 Nov 2016 (http://volcano.si.edu/volcano.cfm?vn=300270) http://dx.doi.org/10.5479/si.GVP.VOTW4-2013
January 1990–February 1995	Historical record	C	3	Paroxysmal	22 April 1993						Chernomorets and Seynova (2010) Global Volcanism Program, 1993. Report on Sheveluch (Russia). In: Venzke, E (ed.), Bulletin of the Global Volcanism Network, 18:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN199304-300270
March–April 1997	Historical record	C	2								Global Volcanism Program, 1997. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 22:3. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN199703-300270
May–September 1998	Historical record	C	3								Global Volcanism Program, 1998. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 23:5. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN199805-300270
April 1999	Historical record	C	2								Global Volcanism Program, 1999. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 24:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN199904-300270
2001	Historical record	C	4	Extrusive	19–20 May 2001	x	x		x	x	Chernomorets and Seynova (2010) Global Volcanism Program, 2001. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 26:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200104-300270

Table 1 (continued)

Eruption date	Dating methods	Uncertain or certain	VEI	Eruption type	Confirmed lahars	Affected rivers of Shiveluch catchment					References
						Baidarnaya	Kabeku	Mutny	Kamenskaya	Bekesh	
				Extrusive	January 2002	x	x		x	x	KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Chernomorets and Seynova (2010) Global Volcanism Program, 2002. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 27:3. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200203-300270
09 May 2004	Historical record	C		Extrusive-effusive						x	KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Chernomorets and Seynova (2010) Global Volcanism Program, 2004. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 29:5. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200405-300270
27 February 2005	Historical record	C		Paroxysmal		x					KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Ponomareva et al. (2007a,b), Chernomorets and Seynova (2010)
22 September 2005	Historical record	C		Paroxysmal		x					KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Chernomorets and Seynova (2010) Global Volcanism Program, 2005. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 30:8. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200508-300270
29 March 2007	Historical record	C		–			x			x	KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Chernomorets and Seynova (2010) Global Volcanism Program, 2007. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 32:3. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200703-300270
				–	06 May 2007		x			x	KVERT database of active volcanoes in Kamchatka and north Kurile Islands (http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en) Chernomorets and Seynova (2010)

Table 1 (continued)

Eruption date	Dating methods	Uncertain or certain	VEI	Eruption type	Confirmed lahars	Affected rivers of Shiveluch catchment					References
						Baidarnaya	Kabeku	Mutny	Kamenskaya	Bekesh	
											Global Volcanism Program, 2008. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 33:1. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN200801-300270
				–	27 April 2009					x	Chernomorets and Seynova (2010) Global Volcanism Program, 2010. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 35:3. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN201003-300270
28 October 2010	Historical record	C		–	17 November 2010		x				Global Volcanism Program, 2010. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 35:11. Smithsonian Institution. http://dx.doi.org/10.5479/si.GVP.BGVN201011-300270 No information about lahars in this moment, but after the eruption pyroclastic deposits have been eroded by many small lahars (Sergey Chernomorets)
20 November 2010	Observation	C		–							No information about lahars in this moment, but after this event, pyroclastic deposits have been eroded by many small lahars (Sergey Chernomorets) Global Volcanism Program, 2010. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 35:11. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN201011-300270
	Observation	C		–	21 August 2011	x					Meteo-induced small debris flow observed during an expedition (Sergey Chernomorets) Global Volcanism Program, 2013. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 38:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN201304-300270
	Observation	C		–	26 April 2012						Sergey Chernomorets Global Volcanism Program, 2013. Report on Sheveluch (Russia). In: Wunderman, R (ed.), Bulletin of the Global Volcanism Network, 38:4. Smithsonian Institution http://dx.doi.org/10.5479/si.GVP.BGVN201304-300270

Shiveluch volcano: volcanic history and affected or probably affected channels

[a] Girina et al. (2016) state that the current eruption of Shiveluch started in 1980 and continues to present day with alternation of extrusive and explosive phases. In this case, the eruptions dated after 1980 could be considered as explosive events on the background of the continuing eruption. Shevchenko et al. (2015) notes three distinct periods of extrusive activity: August 1980–December 1981, April 1993–January 1995, and April 2001–present. In between the periods of dome growth, explosive activity and dome destruction have been observed

2010). The most recent eruptions of Shiveluch volcano occurred in 2005 and 2010 (Solomina et al. 2008; http://www.kscnet.ru/ivs/kvert/volc.php?name=Sheveluch&lang=en).

Prehistoric eruptions of Shiveluch volcano have been reconstructed using tephrochronological methods and radiocarbon dating (Gorshkov and Dubik 1970; Braitseva et al. 1997; Ponomareva et al. 1998; Solomina et al. 2008). Calibrated ages suggest activity around 1021–1057, 1430, and 1641–1663 (Table 1). Between this last period and the 1854 eruption, data on Shiveluch activity are rather uncertain (1770, 1739, 1790–1810). Nevertheless, data on spatial and temporal patterns of historical lahars are scarce and remain rather imprecise in general (Table 2). In most of the historical records, no information about the affected rivers is given. In this study, we have therefore assessed past lahar activity in a 7-km-long study reach (approximately N 56° 29′ 41″, E 161° 29′ 32″, altitude between 150 and 350 m a.s.l.) at the foothills of Shiveluch volcano. The site is located ca. 20 km SSE of the active dome of Young Shiveluch and is divided into three sampling sites according to local channel configuration: Kabeku (NW), Bekesh (NNW), and Kabeku channels (with the latter originating as a result of the confluence of Kabeku and Bekesh; Figs. 1 and 3). This particular study site has been selected due to not only reasons of accessability but also as it covers an area for which past process activity has not been studied before.

Climatic data in this region, which is dominated by continental conditions and an absence of Pacific influence (Krestov et al. 2008), are recorded at Klyuchi (N 56° 32′, E 160° 83′; period covered AD 1930–2012; however, data start to become rather incomplete after 1995). Present-day vegetation of the Central Kamchatka Depression reflects the more continental climatic conditions of the area and consists mainly of *Betula platyphylla* forests, conifer populations (*Larix cajanderi* and *Picea jezoensis* trees), and smaller shrubs of the alpine tundra (Krestov et al. 2008; Jones and Solomina 2015).

Material and methods

Field analyses

The dendrogeomorphic reconstruction of past lahars in the Bekesh and Kabeku channels was performed at elevations between 150 and 350 m a.s.l., in areas with clear signs of past lahar activity (Fig. 2). For this purpose, 236 increment cores and 22 cross sections were systematically sampled from 126 disturbed *L. cajanderi* trees along Bekesh and Kabeku channels and in the main lahar channel below their confluence (Fig. 3). All sampled trees showed clear external signs of disturbances caused by past lahar activity, such as injuries, tilted stems, stem burial, and/or root denudation (see Stoffel and Bollschweiler 2008 or Stoffel and Corona 2014 for recent reviews). In addition, 16 cross sections from young larches growing on a recently formed lahar terrace have been sampled to reconstruct the minimum age of this landform and thus indirectly the age of the last destructive event. In a subsequent step, 26 trees which have not been affected by past lahar activity or any other geomorphic process were sampled to build a local reference chronology representing undisturbed growth (i.e., climatic influence and possible disturbances by insects).

In general, at least two increment cores (Ø 5.5 mm, in the flow direction of events and opposite side) were extracted using increment borers. Sampling height was determined according to the external disturbance of each tree. Injured trees

Table 2 Recorded or supposed lahars occurred at Shiveluch volcano since AD 1854 (Chernomorets and Seynova 2010; updated with unpublished records from S. Chernomorets)

Recorded or supposed lahars	Type of eruption	Affected rivers
1–2 March 1854	Paroxysmal	Baidarnaya, Kabeku, Mutnyi lahars reached Kamchaka and Elovka rivers
12 November 1964	Paroxysmal	Baidarnaya, Kamenskaya, Kabeku
22 April 1993	Paroxysmal	Unknown
19–20 May 2001	Extrusive	Baidarnaya, Kamenskaya, Kabeku? Bekesh
January 2002	Extrusive	Baidarnaya, Kamenskaya, Kabeku? Bekesh
9 May 2004	Extrusive-effusive	Bekesh
27 February 2005	Paroxysmal	Baidarnaya
22 September 2005	Paroxysmal	Baidarnaya
29 March 2007	Unknown	Kabeku, Bekesh
6 May 2007	Unknown	Kabeku, Bekesh
27 April 2009	Unknown	Bekesh
17 November 2010	Unknown	Kabeku
21 August 2011	Unknown	Unknown
26 April 2012	Unknown	Unknown

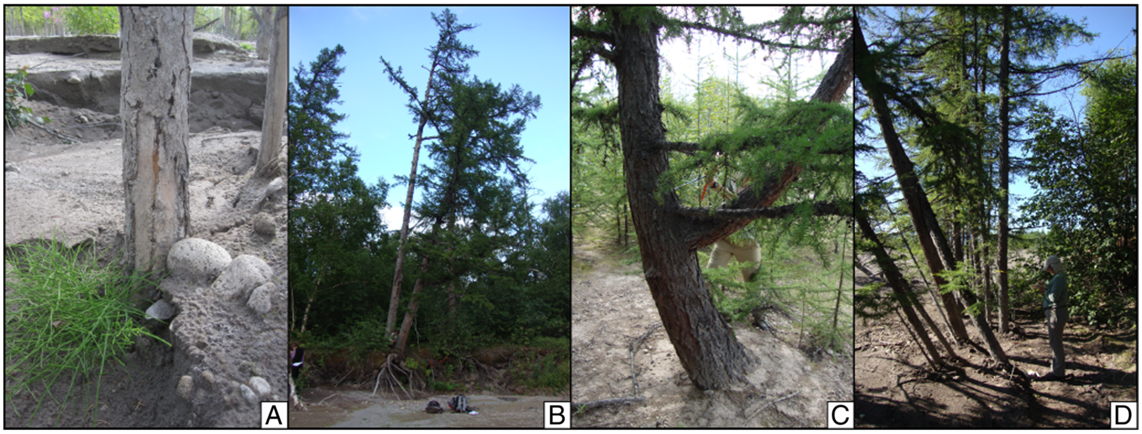
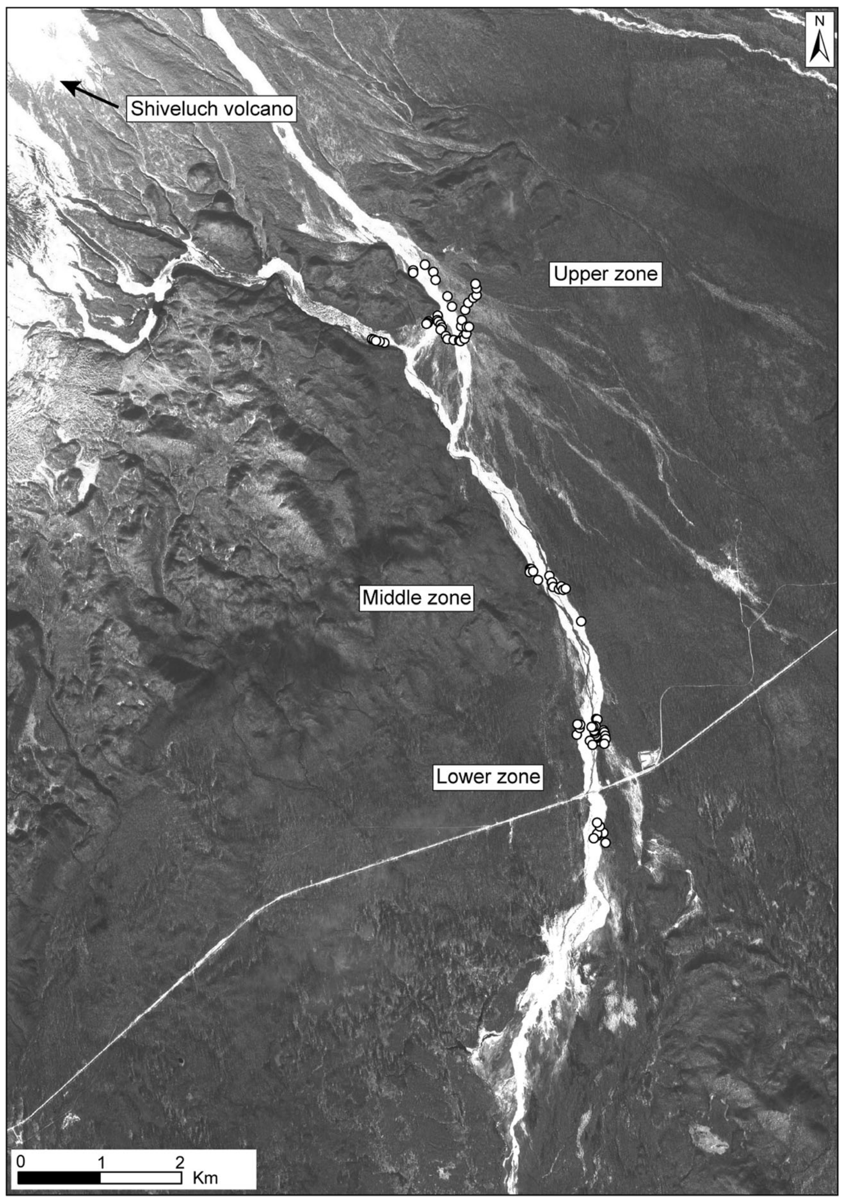


Fig. 2 Disturbed *Larix cajanderi* trees sampled along Bekesh and Kabeku channels (August 2012). From left to right, external disturbances showing injury (**a**), burial (**b**), root exposure (**c**), and tilting (**d**)

Fig. 3 Distribution of sampled trees and subdivision of the study site



were sampled at wound height at both sides of the overgrowth, with particular attention given to the overgrowing callus and related tangential row of traumatic resin ducts (TRDs; Bollschweiler et al. 2008; Stoffel and Bollschweiler 2008; Schneuwly et al. 2009a,b). Buried trees and trees showing root denudation were sampled at the stem base (Kogelnig-Mayer et al. 2011), as close to the ground as possible, in order to guarantee the highest number of rings. Tilted trees were sampled at the height of the maximum curvature, where compression wood generally forms (Braam et al. 1987; Silhan et al. 2015). If a tree was dead, neighboring trees were sampled as close to the trunk base as possible in order to date possible growth releases occurring in the tree-ring series (Stoffel and Bollschweiler 2008). Damaged trees were recorded and described using standard description sheets (Stoffel et al. 2013). Description focused on (i) tree species, (ii) observed external disturbances (such as morphology, height, and size of the disturbance), (iii) tree location, (iv) tree diameter at breast height (DBH), (v) position and height of the extracted cores or cross sections, and (vi) information about neighboring trees.

For 16 *L. cajanderi* trees growing on a relatively young lahar terrace, we estimated the minimum age of the terrace using two different approaches suggested by Pierson (2007): The first approach was based on the five oldest, and the second one based on the five largest sampled trees. For the dating of young geomorphic forms, Pierson (2007) takes into account (i) the germination lag time (GLT) of the sampled trees (i.e., the time interval between the last devastating event and the first germination of young trees) and (ii) the time a tree needs to grow to sampling height (if trees were not cored or cut at their trunk base). To obtain the real age of the terrace, Pierson (2007) suggests adding 6 ± 3 years for the five largest sampled trees and 5 ± 3 years for the five oldest sampled trees. The time elapsing between the formation of a new terrace and the first germinations appears to be very fast on lahar deposits as a result of high soil fertility (Pierson 2007; Bollschweiler et al. 2010; Van der Burght et al. 2012), so that we used a GLT of 2 years in our study.

Sample analysis

Sample analyses followed the procedures described by Stoffel and Corona (2014). Individual steps included the sanding of samples, counting, measuring, and correcting of tree-ring series. Tree-ring widths were measured using a Leica microscope connected to a LINTAB table and running the Time Series Analysis and Presentation (TSAP; Rinntech 2012) software with a resolution of 0.001 mm.

The reference chronology, representing undisturbed growth conditions in the Shiveluch area for the period AD 1737–2012, was used to cross-date and correct growth ring series of disturbed trees so as to identify (i) possible measuring errors, (ii) missing, and/or (iii) false rings. After correction and absolute dating of the tree-ring series, each sample was analyzed under the microscope and mechanical disturbances were listed in an event table. Attention was paid to injuries and related callus tissue, tangential rows of TRDs, abrupt growth suppression or release, as well as the formation of compression wood (Stoffel et al. 2010; Stoffel and Corona 2014). Intensities have been added to each reaction (weak, medium, strong; Kogelnig-Mayer et al. 2011), and the seasonality of damage infliction has been noted in the case of TRDs or callus tissue (Stoffel et al. 2005a,b).

Lahar reconstruction

To discriminate between real lahar signals and noise related to external factors (such as climatic variations, animal, or anthropogenic activity), we associated two statistical values to each year of the reconstruction, namely the I_t value (Shroder 1978) and the weighted index W_{It} (Kogelnig-Mayer et al. 2011), both taking account of the amount of responses in a certain year with respect to the amount of sampled trees being alive in this year. The weighted index W_{It} differs from the I_t value insofar as it also takes account of the intensity of the growth disturbances (GDs) occurring in a given year.

We then determined thresholds for the minimum number of GD and the minimum values of the statistical indices to accept reactions in a specific year as a lahar by comparing our values with those from other studies focusing on comparable geomorphic processes (i.e., Kogelnig-Mayer et al. 2011; Corona et al. 2012; Schneuwly-Bollschweiler et al. 2013; Stoffel et al. 2013). As no standard threshold values exist for lahars, we considered the statistical values observed in years with existing historical records of lahars as yet another reference. The values obtained with the latter approach were indeed very similar to those obtained in the literature and for snow avalanches (Kogelnig-Mayer et al. 2011; Corona et al. 2012), debris flows (Kogelnig-Mayer et al. 2011; Schneuwly-Bollschweiler et al. 2013), landslides (Corona et al. 2012), or snow avalanches (Stoffel et al. 2013). For the reconstruction of lahar activity at Shiveluch volcano, we applied variable thresholds for GD and statistical values depending on changes in sample size over time as suggested by Corona et al. (2012). Table 3 summarizes the threshold values used in this study for sample size, number of GD, as well as for I_t and W_{It} indices.

Table 3 Threshold values for GD and statistical indices

Sample size	No. of GD	W_{It}	I_t
1–19	≥2	≥0.60	≥4
20–49	≥2	≥0.40	≥5
50–99	≥3	≥0.70	≥6
100–125	≥7	≥1.00	≥5

Reconstruction of event seasonality

The seasonal timing of eight historical lahars occurred in 1964, 1993, 2002, 2004, 2005, 2007, 2009, and 2011 (Chernomorets and Seynova 2010) was contrasted with precipitation records from the nearest meteorological station located at Klyuchi (N 56° 32′, E 160° 83′) so as to determine the influence of and possible threshold values for rainfall-triggered events. We therefore analyzed antecedent rainfall totals and snowfall conditions for the 1, 3, and 5 days preceding historical lahars as well as records of volcanic activity, temperature data, and the seasonality of GD as observed in the tree-ring series.

Results

Age structure of trees and nature of GD

The mean age of the 126 disturbed trees was 94 years (STDEV 71 years), with the oldest tree showing 327 and the youngest one 14 rings. The oldest trees are located in the central zone of the study area and at the channel margin, within the first meters of the present-day forest stand. The current shape of the channel seems to bypass the sampling site and can thus explain the significant age of trees in this sector. By contrast, the youngest individuals clearly stand in the upper and lower zones of the study reach, where trees growing directly along the channels show a maximum age of 100 years. Trees sampled south of the present road connecting Klyuchi and Ust'-Kamchatsk show maximum ages of 75 years. Colonization is very important after the 1940s at the site with 50% of all sampled trees showing innermost rings between AD 1941 and AD 1999.

Analysis of the 258 tree-ring samples from the Bekesh and Kabeku channels exhibits a total of 508 GD related to past lahar activity (Table 4). Most disturbances were in the form of TRDs being formed around wounds after mechanical damage (37%), followed by abrupt growth decreases (33%) reflecting apex decapitation, stem burial and/or root denudation, as well as sudden growth releases (18%) occurring in surviving trees after the elimination of neighbors. Other types of GD, including compression wood (7%) after stem tilting, or wounds, and/or callus tissue (5%), visible on the increment cores, were much less abundant. In 15% of the samples, we could not find any significant GD after the assumed passage of lahars. In general terms, however, the broad spectrum of internal GD observed in the tree-ring series was clearly reflective of the external disturbances observed in the field (Fig. 2).

Table 4 Growth disturbances associated with lahar activity at Bekesh and Kabeku channels

Injury with callus tissue	26	5%
Traumatic resin ducts (TRDs)	190	37%
Growth suppression	166	33%
Growth release	90	18%
Compression wood	36	7%
Total	508	100%

Analyses on the seasonality of GD were performed with those samples showing wounds, callus tissue, and/or related TRDs. Virtually all wounds and related growth phenomena found in the tree-ring sequences (95%) point to lahar events during the dormancy of trees or at the very beginning of the growing season (early earlywood cells), which means that damage was inflicted sometimes between October of the previous year and May of the year in which the injured ring was formed. This finding suggests that almost all lahar reactions in trees sampled at the foothills of Shiveluch volcano would have been inflicted in winter or spring, whereas only a very small minority of samples (5%) showed reactions in summer and/or early fall. Reactions in the later portions of earlywood and early latewood—corresponding of events in July and/or August—could not be observed at all.

Dating past lahar activity

Although the age of trees sampled at the study site reaches back to AD 1685, the oldest GD occurs at AD 1729. For the period 1729–2012, the thresholds defined for event reconstruction were passed 34 times and allowed the reconstruction of 26 unknown lahar episodes. In addition, we were able to confirm eight events (1964, 1984, 1993, 2004, 2005, 2007, 2009, and 2011) which have been documented previously in local archives (Fig. 4). The contribution of this dendrogeomorphic analysis is most obvious for the more distant past for which evidence of lahars was completely missing. Based on GD and the spatial distribution of affected tress, we could add 21 events which have left clear fingerprints and abundant evidence of lahar activity in vegetation growing along the Bekesh and Kabeku channels. These events include lahars in 1798, 1865, 1884, 1891, 1898, 1908, 1924, 1949, 1954, 1958, 1975, 1978, 1982, 1986, 1987, 1990, 1992, 1995, 1998, 2006, and 2008. In addition, tree-ring records point to five more events, namely in 1901, 1904, 1921, 1976, and 2002. However, we are not equally confident with the dating of these five lahars and hence consider them as probable events because of (i) the less obvious nature and intensity of GD and (ii) the limited number of responding trees. Furthermore, we could not reconstruct four of the known, historical events (1854, 1989, 2001, and 2002) using our tree-ring records.

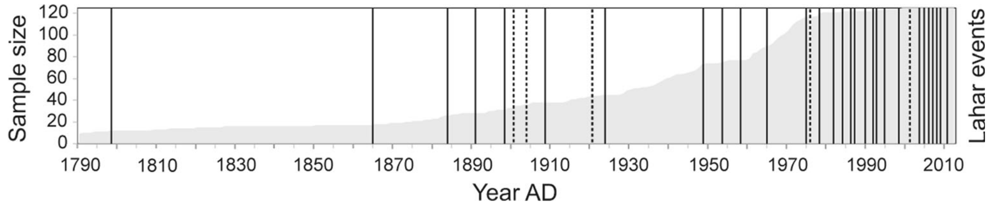


Fig. 4 Number of trees sampled and reconstructed lahars that occurred at Bekesh and Kabeku channels between AD 1729 and 2012. *Bold lines* indicate events with growth disturbances observed in a large number of trees; *dashed lines* represent less-certain events, for which only a limited number of trees preserve evidence

Channel activity and reach of lahars

In the following, we represent the distribution of trees with GD induced by a particular lahar in order to estimate (i) the minimum reach of events and (ii) to disentangle flow paths—and hence channel activity—during past lahar activity. By way of example, the spatial distribution of four significant and representative lahars is shown in Fig. 5d.

The most important lahar(s) in terms of GD occurred after the huge eruption of Shiveluch in November 1964. Lahars were triggered in winter 1964–1965, i.e., during the dormancy of trees, and thus first, strong reactions were observed in the growth ring records of trees in the early earlywood of 1965. The spatial distribution of disturbed trees shows that both headwater channels must have been active in the aftermath of the important volcanic activity of 1964 and that lahars went well beyond the present position of the road and the bridge connecting Klyuchi and Ust'-Kamchatsk (Fig. 5).

By contrast, the lahars of 1987—shown in Fig. 5b—were not documented in archives, whereas trees in the upper, central, and lower parts of the study reach show clear evidence of lahar damage. In this case, lahars were flowing in the Bekesh channel but did not reach the bridge. As shown in Fig. 5c, ten trees were damaged in 1995, with damage being limited to the upper and lower parts of the study reach and activity in both channels. Tree-ring responses in 2004, by contrast, are shown here to confirm a "historical" event with evidence of lahar activity being recorded in 14 trees. It seems that Bekesh was active during this event and that the lahar(s) reached and passed the bridge (Fig. 5d).

Seasonality of lahars and possible triggers

The eight historical events of AD 1964, 1993, 2002, 2004, 2005, 2007, 2009, and 2011 were then further analyzed in terms of precipitation data so as (i) to explain the role of rainfall in the triggering of lahars and (ii) to identify possible thresholds of triggering precipitation events. Seven of these lahars have been confirmed with tree-ring analyses, whereas evidence for the 2002 lahar is limited. Table 5 summarizes the comparison of historical lahars with 1, 3, and 5-day rainfall durations and 1, 3, and 5-day snow depths, as well as with existing records of historical eruptions, temperature data, and seasonality of observed TRDs.

We first of all observe that historical lahars were restricted to periods of volcanic activity and that 6 out of 12 events were clearly unrelated to rainstorms, with <5 mm of precipitation recorded during the 5-day preceding lahars. At the same time, data indicates that existing snowpack seems to have been the most important single source of water for lahar initiation. Even if in the case of the February 2005, September 2005, and March 2007 lahar events, precipitation rates were slightly higher (with 17, 25, and 21 mm, respectively, over a period of 5 days; Table 5), the triggering of lahars itself was for sure favored by the deposition of hot pyroclastic material on an existing snow cover. The existence of a snow cover during the abovementioned events is confirmed by weather data and satellite imagery.

These observations, as well as tree-ring and meteorological evidence of older events, thus suggest that historical lahars were syn-eruptive and that they occurred during periods of volcanic activity at times when snow covered the slopes. The occurrence of rainstorms does not seem, by contrast, to play a significant role in lahar triggering. Furthermore, none of the historical lahars occurred during the growing season of trees (i.e., outside dormancy) or in times without volcanic activity. Therefore, the return period of lahars in the Kabecu and Bekesh valleys likely depends on return intervals of eruptions of Shiveluch volcano.

Deciphering age and process activity on a seemingly young lahar terrace

We also investigated the large lahar terrace located on the left margin of the current Kabeku lahar channel and at an altitude comprised between about 190 and 170 m a.s.l. (Fig. 1). Although the form is larger in extent, we sampled a surface of ca. 0.008 km^2 to estimate the age of this deposit. The investigation was motivated by the fact that the terrace is located around 500 m north of the road linking Klyuchi with Ust'-Kamchatsk and that any knowledge of lahar activity in this area would provide information about processes which could affect the main road and thus pose an important safety hazard. The oldest tree sampled on the terrace has a reconstructed minimum age of 53 years; the youngest tree is, by contrast, 33 years old (mean

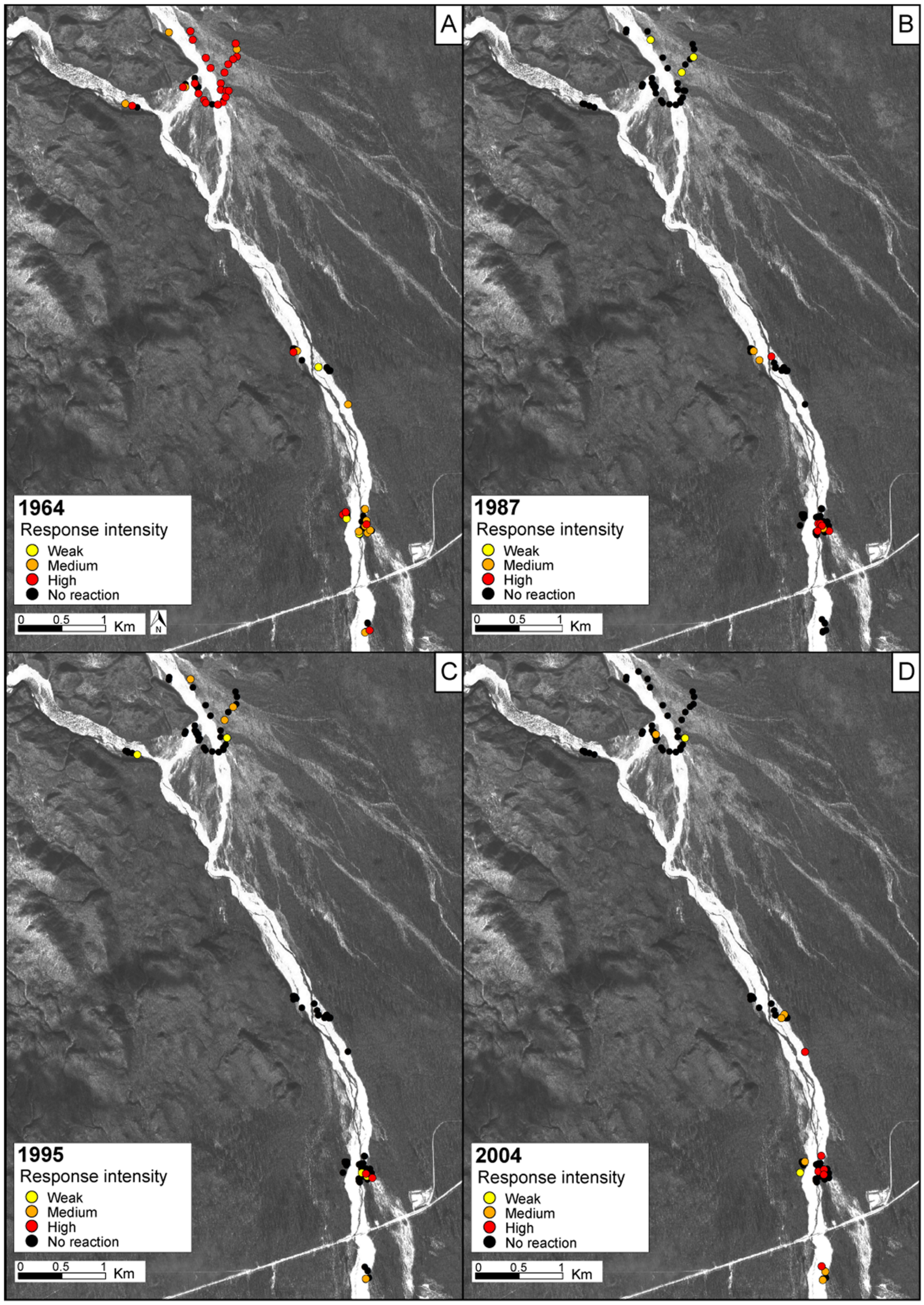


Fig. 5 a–d Spatial distribution of trees damaged by lahars in 1964 (**a**), 1987 (**b**), 1995 (**c**), and 2004 (**d**). The most important lahar(s) in terms of GD were triggered in winter 1964–1965, after the large eruption of Shiveluch volcano on 12 November 1964. Strong reactions were observed in the growth ring records of trees in the first earlywood rows of 1965 (**a**)

age 44 years, STDEV 6 years) when sampled in 2012. However, as all trees exhibit very strong growth suppression with several missing rings during the 1980s as well as branches located at current ground level, we conclude that the current ground surface does not represent the surface on which these trees germinated but points to a substantial sedimentation event in this sector some 30 years ago. This finding is confirmed by aerial pictures indicating the presence of fresh lahar deposits in this area during the same period. As a consequence, the sampling height at <5 cm from the ground level in 2012 is not therefore presenting the germination level but the level of the new surface formed by the event in the 1980s. In addition, the intensity of the widespread growth decrease observed in the growth ring records of all trees sampled suggests massive sedimentation (<1 m) at the site, which also means that one needs to add at least 5–10 years to the age at current ground level to take account of the time needed for trees to reach a height corresponding to the assumed sedimentation depth, yielding estimated minimum ages of trees and an assumed colonization of the original deposit between the late 1940s and early 1950s (Fig. 6, Table 6).

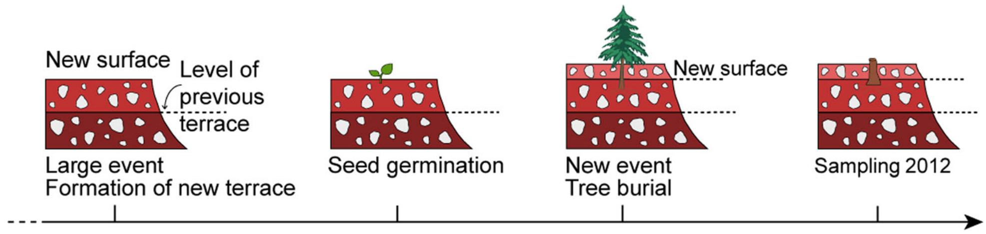
Table 5 Possible hydrometeorological triggers of historical lahars at Shiveluch volcano

Historic lahar(s)	Volcanic activity	Response year (AD)	Seasonality of TRDs	1-day (mm)	3-days (mm)	5-days (mm)	1-day snow depth (mm)	3-days snow depth (mm)	5-days snow depth (mm)	Max/min T (°C)	References
12 January 1964	12 November 1964	1965	D	0	0	0	No data	No data	No data	−9.5/−20.3	Chernomorets and Seynova (2010)
22 April 1993	22 April 1993	1993	D	0	0	3	381	460	511	−0.6/−8.1	Chernomorets and Seynova (2010), The Global Volcanism Program
January 2002 (imprecise)	15 December 2000–22 May 2001	2002	EE								Chernomorets and Seynova (2010), The Global Volcanism Program
24 January 2002				9.6	12.9	12.9	1260	1341	1341	−5.7/−17.5	Highest precipitation observed in January 2002
09 May 2004	09–10 May 2004	2004	D	0	0	4.2	640	790	899	4.8/−1.6	Chernomorets and Seynova (2010), The Global Volcanism Program
27 February 2005	27–28 February 2005	2005	D	7.8	12.1	16.8	1199	1151	1140	0.3/−8.2	Chernomorets and Seynova (2010), The Global Volcanism Program
22 September 2005	22 September 2005			15.2	23.8	25.2	0	0	0	8.1/0.5	Chernomorets and Seynova (2010), The Global Volcanism Program
29 March 2007	29 March 2007	2007	D	0	18.5	21.1	1069	991	800	2/−3.4	Chernomorets and Seynova (2010), The Global Volcanism Program
06 May 2007	05–07 May 2007			0	0	0.6	429	610	711	11.7/−1.1	Chernomorets and Seynova (2010), The Global Volcanism Program
27 April 2009	March–April 2009	2009	D	0	0.3	0.5	739	820	841	6.5/−1.5	Chernomorets and Seynova (2010), The Global Volcanism Program
17 November 2010	28 October–31 December 2010	2011	D	No data	No data	No data	79	79	89	no data	Chernomorets and Seynova (2010), The Global Volcanism Program
21 August 2011	18–21 June, 23 August 2011						0	0	0	19.2/–	Chernomorets and Seynova (2010)

Data represent historic lahars, reported volcanic activity, and rainfall data recorded at Klyuchi meteorological station, located ca. 45 km SW from the sampling site

D dormancy period, *EE* early earlywood cells

Fig. 6 Timeline explaining the age estimation of the lahar terrace, based on the schematic timeline proposed by Pierson (2007) and adapted for the situation at Shiveluch volcano



Discussion

In this study, we reconstruct past lahar activity in the Bekesh and Kabeku channels, at the foothill of Shiveluch volcano in the northern part of the Kamchatka Peninsula, Russia, applying a suite of dendrogeomorphic techniques. Using 258 samples from 126 *L. cajanderi* trees with clear signs of past lahar activity, we reconstruct a time series of syn-eruptive lahar activity at the site extending back to the mid-eighteenth century and provide evidence on the timing, return intervals, reach, and triggers of past lahars.

Most of the observed disturbances were in the form of tangential rows of TRDs (37%), which appear in conifers within 2 or 3 weeks after mechanical damage and thus allow dating of lahars with seasonal and sometimes up to monthly precision (Stoffel et al. 2005a,b; Stoffel 2008; Stoffel and Corona 2014). Thus, the simultaneous formation of TRDs in several trees along the Bekesh and Kabeku channels does not only allow us to date past events with precision but also is useful for constraining the spread and reach of individual events. The presence of wounds and callus tissue—visible in 5% of the samples—complements the results of the TRD analysis and confirms the reconstruction of past lahars at the site. Around one in two GDs was in the form of abrupt changes in radial growth (i.e., decreases and releases, visible in 51% of the samples), reflecting massive stem burial, root denudation, or the elimination of neighboring trees by solid lahar material (e.g., logs, debris, and boulders). Based on the field observations and results of tree-ring analyses, we identify two types of flows able to produce tree damage. Trees with injuries, callus tissue, and TRDs are likely damaged by bouldery lahars (similar to debris flows) with substantial amounts of coarse and suspended particles. By contrast, we interpret the occurrence of growth suppressions and compression wood as being a reaction to flow with more diluted phases (e.g., hyperconcentrated flows; Vallance 2005).

We also confirm that the I_t and W_{It} values suggested by Corona et al. (2012), Franco-Ramos et al. (2013), or Schneuwly-Bollschweiler et al. (2013) are very reliable for lahar studies as well and allow discrimination of real signals induced by geomorphic processes from background noise (e.g., fraying or browsing by rodents, thunderstruck, naturally falling neighboring trees). Nevertheless, we still call for more research and further methodological improvements when it comes to the identification of ideal and highly reliable threshold values for other processes, as well as for optimal sample size and sampling strategies which are considering differences in tree species and geomorphic processes (Stoffel et al. 2013; Trappmann et al. 2014; Morel et al. 2015).

Analyses of the seasonality of TRDs and callus tissue reveal the importance of the winter half-year on lahar occurrence. About 95% of the reactions were observed in the early earlywood cells of the new growing season, thus pointing to lahar occurrence sometimes between the end of the previous vegetative period of the previous year (i.e., October) and the beginning of the new growing season in which the ring was formed (i.e., May). This finding suggests that most lahars occur in winter or spring when volcanic eruptions cause a sudden melting of the snow cover on the volcano and the remobilization of stored volcanic material. Historical lahars have been shown to be syn-eruptive and that they originate due to the sudden melting of snow by hot volcanic material. At the same time, we have shown that precipitation events alone do not play a decisive role in lahar triggering. Therefore, the return period of lahars likely depends on the return interval of eruptional phases of Shiveluch volcano.

The results of this research confirm the potential of dendrogeomorphic techniques in volcanic and lahar research,

Table 6 Reconstruction of the minimum age of a seemingly young lahar terrace using two different approaches suggested by Pierson (2007), based on the five oldest and five largest sampled trees

Approach	GLT (years)	Estimation of minimum age of the primary terrace
Mean of 5 largest trees and GLT estimation (expert approach)	2	AD 1951 ± 3 years
Mean of 5 oldest trees and GLT estimation (expert approach)	2	AD 1948 ± 3 years
Mean of 5 largest trees and GLT estimation from Pierson (2007)	6 ± 3	AD 1948 ± 6 years
Mean of 5 oldest trees and GLT estimation from Pierson (2007)	5 ± 3	AD 1946 ± 6 years

We used germination lag times (GLT) suggested by Pierson (2007) as well as estimated GLT using an expert approach as already suggested in recent studies performed in the Mexican Volcanic Belt by Bollschweiler et al. (2010), Stoffel et al. 2010), and Franco-Ramos et al. (2013, 2016). The widespread presence of TRDs is a reliable tool for event detection as well as the determination of event seasonality, as pointed out in recent works (e.g., Bollschweiler et al. 2008; Stoffel and Hitz 2008; Schneuwly et al. 2009a,b; Ballesteros et al. 2010b; Arbellay et al. 2014).

At the same time, however, we realize that the reconstruction of past lahars with dendrogeomorphic techniques is still a new application to tree-ring research. In fact, by contrast to other paleohydrological or paleohydraulic applications (Borga et al. 2014; Ballesteros et al. 2010a,b; Rodriguez-Morata et al. 2016), our reconstruction yielded limited information on event magnitudes and failed to provide evidence of five reported lahars. These shortcomings are likely due to (i) insufficient tree sampling and sample size (limited during the AD 1854 event); (ii) the ever-changing vertical and lateral shape of lahar channels over time; (iii) the fact that small, water-rich flows may not damage trees; (iv) local events could have occurred in only one channel and not in others (Solomina et al. 2008) or may have been beyond the spatial extent of the study area; and (v) the fact that destructive events can remove all signs of previous events (Mayer et al. 2010). For the above reasons, we were able to determine a minimum frequency of lahar events that occurred at Shiveluch volcano along the Bekesh and Kabeku channels and over the past few centuries.

Although we were not able to estimate the magnitude of the lahars, we attempted to estimate the minimum reach for each reconstructed event based on the spatial distribution of damaged trees. Almost one in three (13 out of 34) events has reached or passed the road connecting the towns of Klyuchi and Ust'-Kamchatsk, although it is located more than 20 km downstream of the Young Shiveluch eruptive dome, suggesting a frequency of around 5 years for large lahars at the study site. Another 11 events reached at least the lower sampling zone (Fig. 3) located less than 500 m north of the present road. We cannot confirm that these events reached the level of the road as well. By contrast, seven lahars reached at least the central area of the study zone, whereas three events were apparently stopped in the upper zone. Noteworthy, the 10 events which were stopped at higher locations are also those which occurred prior to the 1950s when sample size was limited (<75 trees) and presently living trees were not yet established in the downstream areas of the site. It is possible that the reconstructed minimum reach for these events is related to the restricted sample size rather than to smaller events.

For the reconstruction of the minimum age of the seemingly young lahar terrace, we based our analyses on GD observed in 16 relatively young larches, estimated values for germination lag time, and depositional depth of the lahar deposit. The formation of the initial terrace can be narrowed down to the 1940s–1950s using the approaches suggested by Pierson (2007) (Table 6). This estimate is in good agreement with a presumably larger lahar event which would have occurred prior to the 1940s and which would have swept away part of the vegetation along the channels. This assumption is confirmed by an excessive amount of newly colonizing trees with 50% of the samples used in this study having innermost rings dated to between AD 1941 and 1999.

Conclusions

In this contribution, we present a dendrogeomorphic reconstruction of lahar activity at Shiveluch volcano using disturbed *L. cajanderi* trees growing along two active lahar channels. The combination of geomorphic analyses and dendrochronological dating methods has been demonstrated to be an accurate and reliable tool to increase the knowledge about past lahars that occurred in out-of-reach areas where direct observations are limited or absent. The approach has been fundamental in extending historical records and improving documentation of past activity but has some limitations for constraining magnitude and for identifying all events described in written sources. The approach we followed can provide a minimum frequency of past activity but may not yield a full record of past events.

Despite these limitations, *L. cajanderi* trees have been shown to be a valuable dendrogeomorphic recorder of past lahar activity on Kamchatka Peninsula, allowing the addition of 21 previously unknown events (probably related to unknown eruptive episodes) to the lahar chronology of Shiveluch volcano, as well as the confirmation of 8 historical lahars. We therefore encourage tree-ring research to focus further on lahar reconstruction and to perform more studies on this geomorphic process, so as to extend the approach to new geographic regions or even to disturbed broadleaved trees.

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