Bull Volcanol (1998) 59:490–505

ORIGINAL PAPER

V. V. Ponomareva · M. M. Pevzner · I. V. Melekestsev

Large debris avalanches and associated eruptions in the Holocene eruptive history of Shiveluch Volcano, Kamchatka, Russia

Received: 18 August 1997 / Accepted: 19 December 1997

Abstract Shiveluch Volcano, located in the Central Kamchatka Depression, has experienced multiple flank failures during its lifetime, most recently in 1964. The overlapping deposits of at least 13 large Holocene debris avalanches cover an area of approximately 200 km^2 of the southern sector of the volcano. Deposits of two debris avalanches associated with flank extrusive domes are, in addition, located on its western slope. The maximum travel distance of individual Holocene avalanches exceeds 20 km, and their volumes reach $\sim 3\ km^3$. The deposits of most avalanches typically have a hummocky surface, are poorly sorted and graded, and contain angular heterogeneous rock fragments of various sizes surrounded by coarse to fine matrix. The deposits differ in color, indicating different sources on the edifice. Tephrochronological and radiocarbon dating of the avalanches shows that the first large Holocene avalanches were emplaced approximately 4530–4350 BC. From ~2490 BC at least 13 avalanches occurred after intervals of 30–900 years. Six large avalanches were emplaced between 120 and 970 AD, with recurrence intervals of 30–340 years. All the debris avalanches were followed by eruptions that produced various types of pyroclastic deposits. Features of some surge deposits suggest that they might have originated as a result of directed blasts triggered by rockslides. Most avalanche deposits are composed of fresh andesitic rocks of extrusive domes, so the avalanches might have resulted from the high magma supply rate and the repetitive formation of the domes. No trace of the 1854 summit failure mentioned in historical records has been found beyond 8 km from the crater; perhaps witnesses exaggerated or misinterpreted the events.

Editorial responsibility: D. A. Swanson

Vera V. Ponomareva (✉) · Ivan V. Melekestsev
Institute of Volcanic Geology and Geochemistry, Piip Blvd., 9, Petropavlovsk-Kamchatsky, 683006 Russia
e-mail: ivgg@svyaz.kamchatka.su

Maria M. Pevzner
Geological Institute, Pyzhevsky per., 7, Moscow, 109017 Russia

Key words Volcanic debris avalanches · Repetitive flank failures · Shiveluch Volcano · Tephrochronology · Radiocarbon dating · Kamchatka · Russia

Introduction

Slope failure of a volcanic edifice can produce a voluminous and extremely mobile debris avalanche that travels beyond the volcano at high velocity (Siebert 1984, 1996). Such avalanches can thus be hazardous and sometimes occur without distinct precursors on both active and extinct volcanoes (Siebert 1996; Melekestsev and Braitseva 1984). Therefore, volcanoes that repeatedly produced avalanches are of particular interest (Palmer et al. 1991; Beget and Kienle 1992; Moore et al. 1994). In Kamchatka several volcanoes, including Shiveluch, Bezymianny, Kamen′, Taunshits, Bakening, and Mutnovskii, have experienced large sector-collapse events (Melekestsev and Braitseva 1984; Melekestsev at al. 1990; Belousov 1995; Melekestsev and Dirksen 1997). But only Shiveluch, famous for its 1964 flank failure followed by an eruption (Gorshkov and Dubik 1970; Belousov 1995), experienced multiple debris avalanches during its lifetime (Belousova and Belousov 1994; Ponomareva and Pevzner 1994, 1995).

Documenting and dating Holocene debris avalanches is part of our ongoing study of the Shiveluch eruptive history (Melekestsev et al. 1991; Ponomareva and Pevzner 1996; Pevzner et al. 1998). Detailed geological and tephrochronological studies, which started in 1978, allow us to identify and date these debris avalanches and study the juvenile deposits of associated eruptions. This paper presents a detailed account of the large prehistoric Holocene debris avalanches and landslides, including their stratigraphic positions, ages, areas, travel distances, and other parameters. The interpretation of new air photos, and our ongoing field work, allow us to study in detail the topography and stratigraphy of the 1964 deposits and to suggest a new interpretation of the formation of the 1964 debris avalanche that could to some extent be applied to older avalanches as well.

General description and historical eruptions of Shiveluch

Shiveluch Volcano (Fig. 1), situated in the Central Kamchatka Depression in the supposed conjunction zone of the Aleutian and Kuril-Kamchatka island arcs (Fig. 2), is considered to be the northernmost active volcano of Kamchatka. It is one of the most prolific explosive centers of Kamchatka, with a magma discharge of approximately 36×10^6 tons per year, an order of magnitude higher than that typical of island arc volcanoes (Melekestsev et al. 1991). Shiveluch is a composite volcanic edifice. Late Pleistocene Old Shiveluch stratovolcano was partly destroyed by a large eruption that formed a caldera 9 km across. Young Shiveluch eruptive center is nested in the caldera (Fig. 1). The present altitude of Old Shiveluch is 3283 m, and the summit of the active Young Shiveluch is approximately 2800 m a.s.l. The maximum height of the edifice above its surroundings is more than 3200 m.

Young Shiveluch is composed of multiple coalesced extrusive domes, surrounded by agglomerate mantles and short but thick (up to 100 m at the front) lava flows. Its activity during the Holocene has been characterized by plinian eruptions alternating with periods of dome growth. Several extrusive domes were emplaced at the volcano's foot, including the Late Pleistocene Semkorok domes at the southeastern base and the Holocene Karan domes at the western slope of Old Shiveluch (Fig. 1). The products of Young Shiveluch are dominantly magnesian andesite (Melekestsev et al. 1991).

Written records of the Shiveluch activity date back to 1739 and report on the eruptions in 1739, 1790 (1793), and between 1790 and 1810, but this information lacks certainty (Gorshkov and Dubik 1970). More reliable records begin in 1854 when a large eruption accompanied by voluminous ashfall and failure of the summit was recorded (Ditmar 1890), although our studies show that this description is not precise. The next eruption (formation of a dome and its subsequent destruction accompanied by pyroclastic flows) occurred in 1879–1883. Later eruptions took place in 1897–1898, 1905, 1928–1929, and 1944–1950, and resulted in several extrusive domes and minor ashfalls (Gorshkov and Dubik 1970; Meniailov 1955).

A large plinian eruption of Shiveluch occurred in 1964. It began with the formation of a large debris avalanche deposit (Figs. 1, 3), first interpreted to be the result of a directed blast (Gorshkov and Dubik 1970; Bogoyavlenskaya et al. 1985; Melekestsev et al. 1991) and later reinterpreted as the result of a sector collapse (Belousov 1995). The area covered by the 1964 debris avalanche deposit is approximately 98 km^2, its volume was estimated at approximately 1.5 km^3 (Gorshkov and Dubik 1970), and its travel distance approximately 16 km (Belousov 1995). The debris avalanche deposits resemble those of Mount St. Helens (Bogoyavlenskaya et al. 1985; Belousov 1995). Failure of the edifice triggered a minor phreatic explosion (0.01 km^3 of ash; Belousov 1995) followed by a powerful plinian eruption that produced tephra fall and pyroclastic flow deposits with a total volume of 0.6–0.8 km^3 (Gorshkov and Dubik 1970). The eruption formed the present-day crater. An extrusive dome has been growing in the crater since 1980, occasionally producing small block-and-ash flows, landslides, and minor ashfalls (Dvigalo 1984; Gorelchik et al. 1995; Khubunaya et al. 1995; Zharinov et al. 1995).

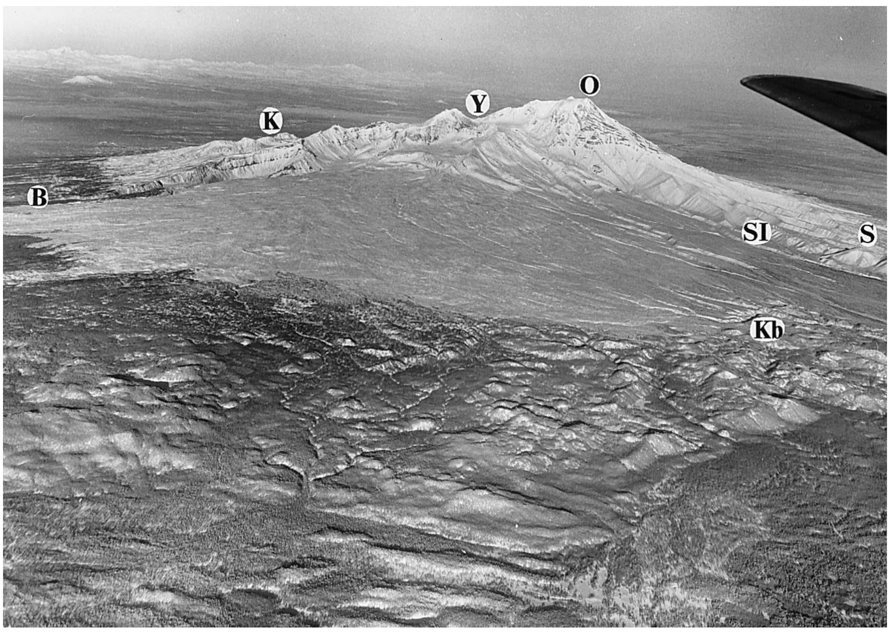

Fig. 1 Shiveluch Volcano viewed from the south. Eruptive centers: *O* Old Shiveluch; *Y* Young Shiveluch; *K* Karan extrusive domes; *S* Semkorok extrusive domes. River valleys: *B* Baidarnaya; *Kb* Kabeku; *SI* Suhoi Il'chinets. The hummocky deposits of the Late Pleistocene debris avalanche are seen in the foreground, and the deposits of the 1964 debris avalanche are nearer the volcano. (Courtesy of N. P. Smelov)

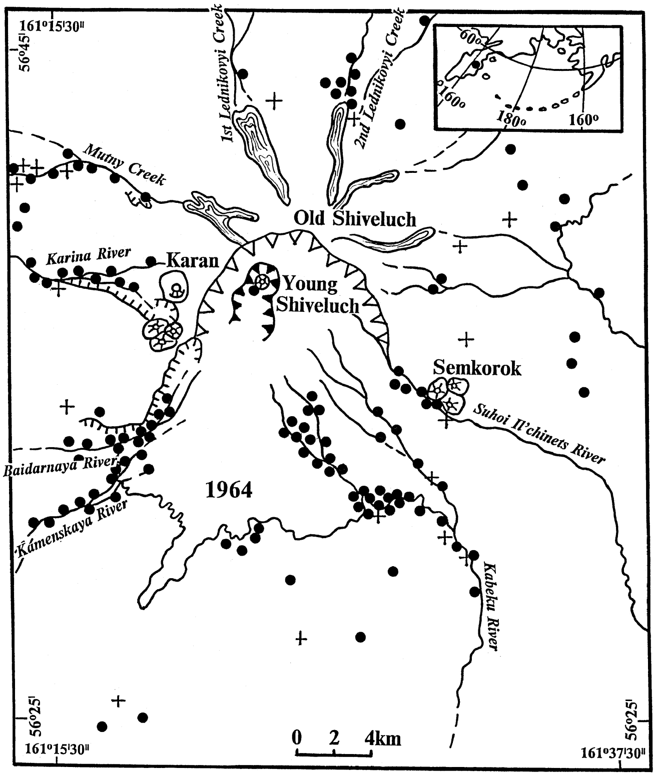

Fig. 2 Location map showing eruptive centers, the rims of the Late Pleistocene caldera and the 1964 crater, river valleys mentioned in the text, and glaciers in the upper streams of some valleys. The outline of the 1964 debris avalanche deposits is shown south of the volcano. Most of the sections measured in 1978–1997 are shown by *dots;* those exposing deposits older than the KL ash from Kliuchevskoi Volcano (5800–6000 years BP; Table 1) are shown by *crosses*

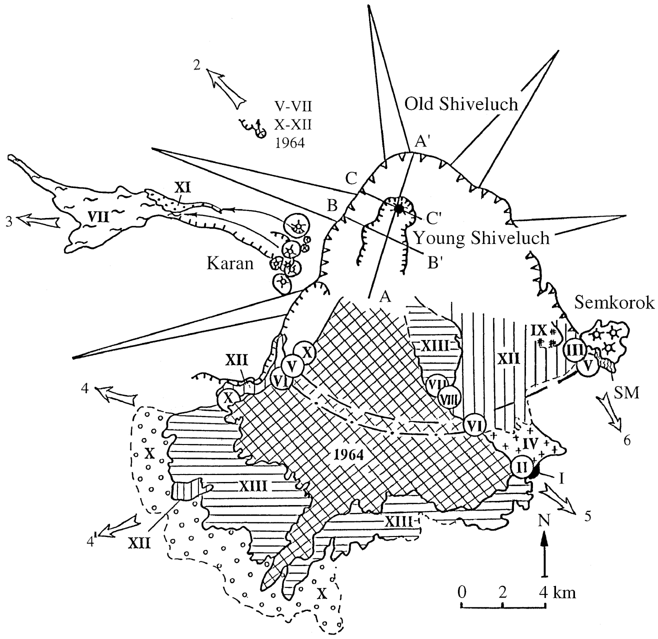

Fig. 3 Map showing the debris avalanche deposits. Mappable avalanche deposits are shown in various fillings; those observed only in sections are shown by *encircled numbers. Arrows* show the location of river valleys: *2* Mutny; *3* Karina; *4* Baidarnaya; *4'* Kamenskaya; *5* Kabeku; *6* Suhoi Il'chinets. The numbers of the debris avalanche units and river valleys coincide with those in Fig. 6. See text for explanations. *Dashed lines* show the supposed borders of debris avalanche deposits. *A–A', B–B'*, and *C–C'* are the lines of the profiles in Fig. 12. *SM* Agglomerate mantle of Semkorok extrusive domes

Before the 1964 eruption researchers at Shiveluch already had paid attention to peculiar deposits that are composed of large angular rock fragments supported by coarse-grained matrix and exposed in deep valleys at the southern slope of the volcano. These deposits were then taken for Holocene moraines (Meniailov 1955). After the 1964 eruption, it became obvious that these older deposits resembled those of the 1964 debris avalanche. They were reinterpreted as directed blast deposits (Gorshkov and Dubik 1970). The oldest deposit of this kind, which forms a large apron at the southern foot of the volcano with hummocks up to 150–200 m high (Fig. 1), was believed to be associated with the eruption that formed the large crater of Old Shiveluch supposedly approximately 30000 ^{14}C years BP (Melekestsev at al. 1991; Braitseva et al. 1995).

The deposit formed during the initial stage of the 1964 eruption called "agglomerate of directed blast" by Gorshkov and Dubik (1970) and "debris avalanche" by Belousov (1995) is very similar to most of the debris avalanche deposits reported in the literature (Voight et al. 1981; Siebert 1984, 1996; Glicken 1986; Ui et al. 1986; Francis and Wells 1988; Siebe et al. 1992). Although the eruption itself was not witnessed, we agree in general with Belousov (1995) and believe that this deposit formed as a result of a large rockslide. Older similar deposits likely had the same genesis. The deposits of the prehistoric debris avalanches have similar characteristics, such as hummocky surface and poor sorting and grading, with abundant angular to subrounded heterogeneous rock fragments of various sizes in a coarse to fine matrix. The deposits of different units differ in color, indicating that different parts of the edifice were involved in landslides, but all of them are patchy due to various colors of individual rock fragments or blocks. The outer edges of some of the avalanches form marginal levees several meters thick, whereas those of the other avalanche deposits gradually pinch out.

A subunit 1–3 m thick characterizes most of the debris avalanches, consisting of more thoroughly mixed sandy material with abundant multi-colored subangular debris and scattered pumice lapilli. This subunit can underlie a typical avalanche deposit, be interlayered with portions of certain debris avalanches, or occur beyond the margin of a debris avalanche.

The character of the basal contact of a debris avalanche differs in various parts of an avalanche. In some places an avalanche seems to slide over older bedded deposits without destroying bedding. In other places the avalanche disrupts underlying deposits and even piles them up to form folds near its outer edge. Originally consisting of dry rock debris, some avalanches could incorporate snow or contain large blocks of frozen rocks (Gorshkov and Dubik 1970).

Study methods

Mapping

Interpretation of 1:30000 scale air photos allows us to examine the topography of the 1964 deposits and map other deposits with hummocky topography slightly smoothed by later pyroclastic products. During field work the areas of hummocky relief were studied, as were small landslide deposits and craters in order to verify the units identified on the air photos. Figure 3 shows all the mappable debris avalanche deposits. Most occur on the southern slopes of the volcano, their distribution having been determined by the scarps of the Late Pleistocene crater. The distal edges of most avalanche deposits are buried by younger pyroclastic and lahar aprons, and their exact areas could not be determined. Nevertheless, at least three avalanches were obviously larger than that of 1964. In addition, two debris avalanche deposits and a large horseshoe-shaped crater were mapped on the western slope of Old Shiveluch. They are thought to be associated with activity of the Karan domes. A small crater and associated landslide deposits were identified in the valley of Mutny River. Some debris avalanche deposits are overlain by a thick cover of younger pyroclastic material and can be observed only in stream banks (Figs. 3, 4).

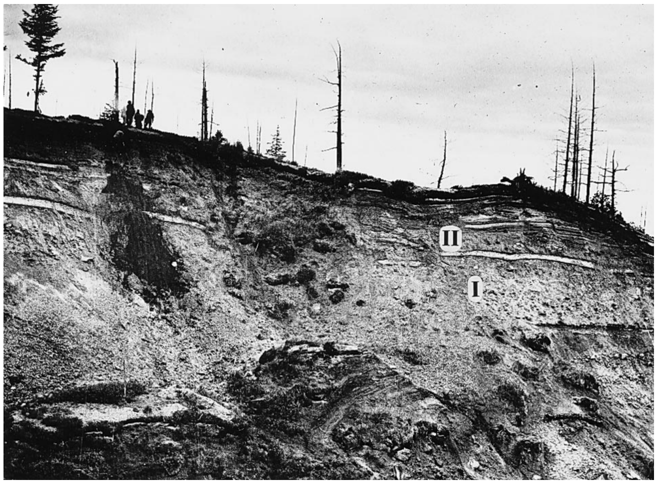

Fig. 4 Deposits of debris avalanches I and II interlayered with pumice fall layers and soils in the Kabeku Valley. Forest destroyed by the 1964 pumice fall. (Courtesy of L. D. Sulerzhitsky)

Most pumice-fall layers produced by Shiveluch look very similar and are difficult to discriminate in many sections. Direct tracing of ash layers from section to section was helpful. We used the following regional marker ash layers as time-markers for the Shiveluch stratigraphy (Table 1): B_{1956}, SH_1, SH_2, SH_3, KS_1, SH_5, SHdv, KHG, and KZ. These layers were identified at Shiveluch and correlated using data from Braitseva et al. (1996, 1997a, b). In addition, we identified several local marker ash layers: KL from the initial eruptions of Kliuchevskoi Volcano and PL from Plosky Volcano (Braitseva et al. 1995), as well as a bed of unique high-

Tephrochronology

The Holocene pyroclastic sequence at the foot of Shiveluch is dominated by pumice-fall layers separated by soil or sandy loam horizons as well as several marker ash layers from other volcanoes (Figs. 4, 5). It is underlain by glacial or pre-Holocene volcanogenic deposits and is well exposed in the deep valleys. Even if the eruptions followed each other in short time intervals, e.g., the 1944–1950 and 1964 Shiveluch eruptions and the 1956 Bezymianny eruption between them, their ashes are still separated by distinct layers of soil or sandy loam. That is why we think that pyroclastic material that lies directly on a debris avalanche deposit is likely to have been emplaced during an eruption immediately following the avalanche, rather than significantly later. Most of the avalanches spread southward, whereas tephra of the related eruption may have been dispersed in other directions. Therefore, the correlation of fall units is very important for fitting the avalanche deposits in distant valleys into the overall stratigraphic succession and for identifying deposits of eruptions associated with pre-historic debris avalanches.

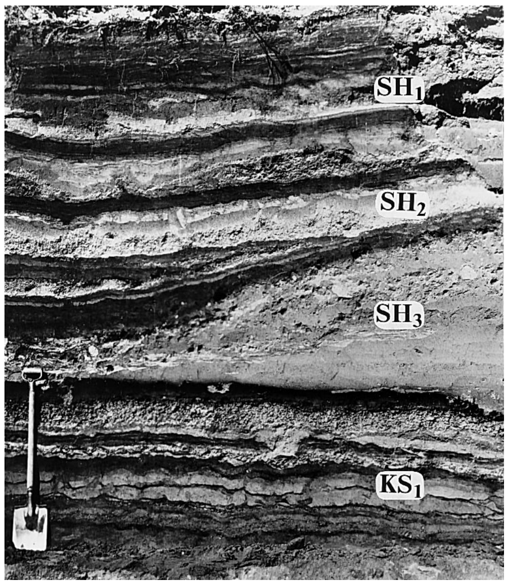

Fig. 5 Upper part of the Holocene pyroclastic sequence at the southern foot of Shiveluch Volcano corresponding to the past 2000 years. For codes and ages of marker ash layers see Table 1. (Courtesy of L. D. Sulerzhitsky)

Table 1 Holocene key-marker ash layers at the foot of Shiveluch volcano, Kamchatka

Source volcano	Code	Ages (^{14}C years BP)	Calendar ages	Description	Composition[a]	Characteristic features
Shiveluch	SH_{1964}		AD 1964	White pumice lapilli	A	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol
Bezymianny	B_{1956}		AD 1956	Gray coarse to fine ash (1–3 cm)	A	Medium K_2O content, presence of Hb
Shiveluch	SH_1	265 ± 18	AD 1641(1652)1663	Thinly stratified white fine to coarse ash	A	Medium K_2O content, high Cr and Sr content, presence of Hb
Shiveluch	SH_2	965 ± 16	AD 1021(1034)1157	Normally graded light gray pumice lapilli and coarse ash	A	Medium K_2O content, high Cr and Sr contents presence of Hb
Shiveluch	SH_3	1404 ± 27	AD 614(653)670	Dirty-yellow pumice lapilli	A	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol
Ksudach	KS_1	1806 ± 16	AD 147(236)317	Pale yellow (upper 1–2 cm gray) fine ash (6–8 cm)	D	Low K_2O content, absence of Hb
Shiveluch	SH_5	2553 ± 46	BC 807(780)524	Yellow pumice lapilli in the western sector and coarse yellow ash in other sectors	A	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol
Shiveluch	SHsp	~3600	~BC 1940	Stratified dark-gray cinder lapilli and coarse ash	B	High K_2O content, presence of Hb and Ph
Shiveluch	SHdv	4105 ± 31	BC 2866(2616)2504	Normally graded pale yellow coarse to fine ash	A	Medium K_2O content, high Cr and Sr content, presence of Hb
Kliuchevskoi	KL	5800–6000	BC 4690–4880	Black or iron-stained ochre coarse ash (0.5–1.5 cm)	BA	Medium K_2O content
Khangar	KHG	6957 ± 30	BC 5926(5769)5711	Bright yellow fine ash (3–4 cm)	D	Medium-high K_2O content, presence of Bi, Hb
Kizimen	KZ	7531 ± 37	BC 6423(6377)6225	Yellow fine ash (1–2 cm)	D	Medium K_2O content, presence of Hb
Plosky	PL	~8600	~BC 7600	Dark-brown coarse ash (1 cm)	BA	High K_2O content

NOTE: The ash layers are listed in chronological order. The ages shown with error are the weighted average radiocarbon ages of the marker ash layers determined from the technique of Stuiver and Reimer (1993) (Braitseva et al. 1997a, b). Other ages are from Braitseva et al. (1995) and Volynets et al. (1997). The calendar ages at 2σ interval are given calculated according to Stuiver and Reimer (1993). In column 5, figures in parentheses are the average thickness of distal marker ash layers. A, BA, D, RD, R – andesite, basaltic andesite, dacite, rhyodacite, rhyolite, respectively. Hb, hornblende; Ol, olivine; Bi, biotite; Ph, phlogopite.
[a] average bulk composition of the ash at the foot of Shiveluch

potassium basaltic ash from Shiveluch (SHsp) described in detail by Volynets et al. (1997). Approximately 200 sections measured in 1978, 1979, 1987, 1990–1993, and 1996–1997 around the volcano (Fig. 2) allow precise correlation of deposits from one sector to another and determination of the stratigraphic position of all debris avalanche deposits with respect to marker ash layers (Fig. 6).

All measured sections are farther than 8 km from the eruptive center, because only the uppermost part of the sequence is exposed closer. For this reason we provide documentation of only those deposits that traveled farther than 8 km from the source. Deposits which are older than 6000 ^{14}C years BP are exposed only in the southern sector beyond the line defined by crosses in Fig. 2. Deposits older than 3100 ^{14}C years BP are not exposed in the Baidarnaya and Kamenskaya rivers (southwestern sector). The pits high on Old Shiveluch in this sector (Fig. 2) expose only fall and surge deposits younger than 7600 ^{14}C years BP.

The section in the upper reach of Mutny River (Fig. 6, section 2) exposes a sequence of small landslide deposits interbedded with surge and ash layers and soils. These landslide deposits have textures typical of those for small non-volcanic landslide deposits and contain soil mixed with rock fragments of various sizes. The surface of the landslide deposits is also hummocky, with individual hummocks up to 1 m high, but their volumes barely exceed 10^5 m^3. The landslides likely correlate with large debris avalanches on the southern and western flanks of the volcano, based on similar stratigraphic position of the deposits.

Radiocarbon dating

To supplement the relative dating of debris avalanche deposits using the marker ash layers, we obtained 19 radiocarbon ages on wood and thin soil layers above and below the deposits (Fig. 6; Table 2). The ^{14}C dating technique used in this study is described by Braitseva et al. (1992, 1993). We used the dates on wood and thin (1–3 cm) soil layers, which formed over a short span of time. Dates from thick soil layers, formed over a long

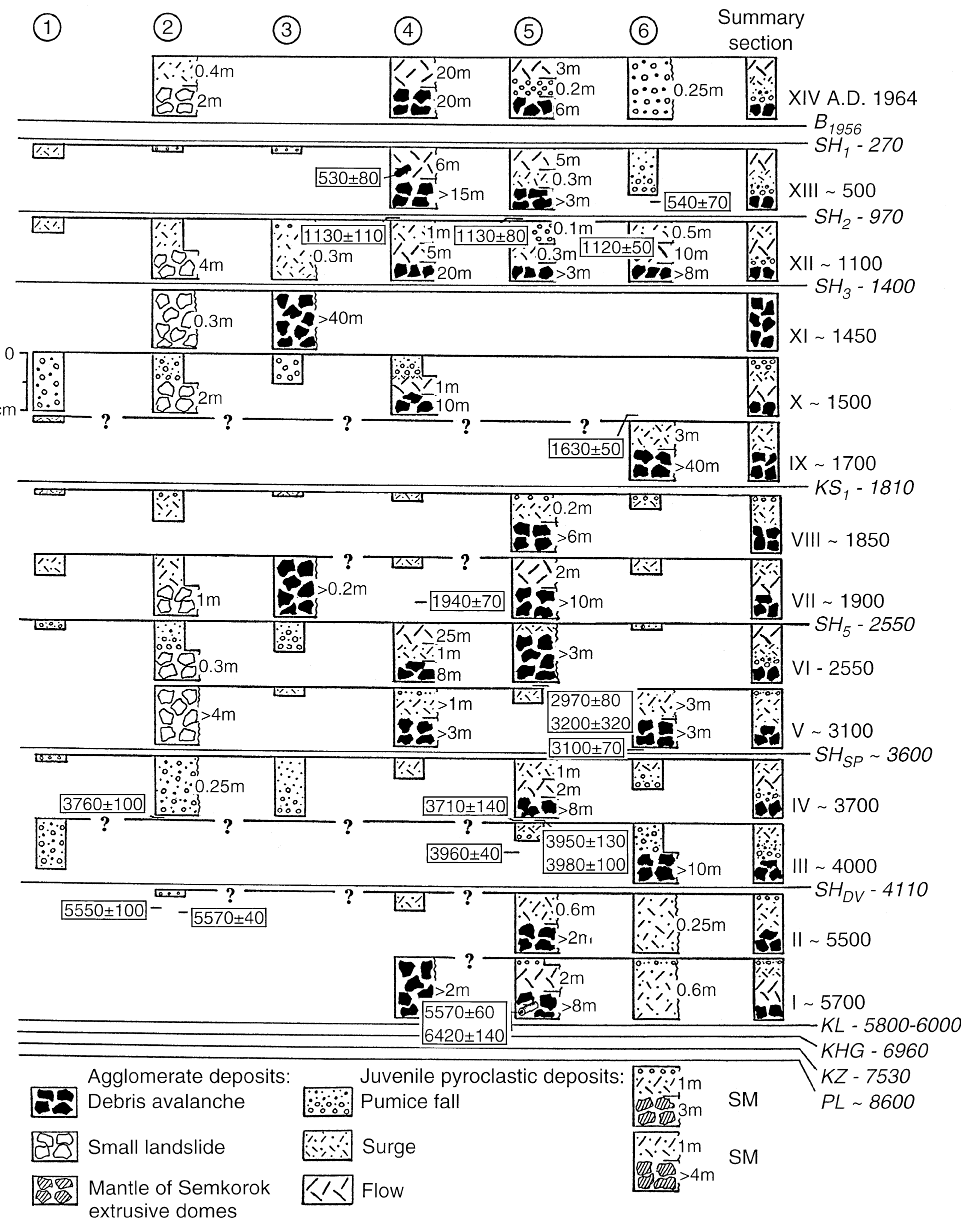

Fig. 6 Stratigraphic position of debris avalanche deposits and pyroclastic deposits of associated eruptions with respect to marker ash layers. The summary sections of the deposits exposed in individual river and creek valleys are arranged from north to southwest: *1* First Lednikovyi; *2* Mutny; *3* Karina; *4* Baidarnaya and Kamenskaya; *5* Kabeku; *6* Suhoi Il'chinets. For debris avalanche deposits Roman numerals and rounded radiocarbon ages are given. Average radiocarbon ages of marker ash layers (Table 1) are rounded to the nearest 10 years. For their codes see Table 1. Radiocarbon dates are shown in boxes (see Table 2). *SM* agglomerate mantle of Semkorok extrusive domes. The deposits of Shiveluch which are not considered in this paper are omitted

time interval, were used only in cases where dates were obtained on successive alkaline extractions (Table 2). In such cases we used the younger date for the soil underlying, and the older date for the soil overlying the deposits. A date obtained on a thick soil or peat layer without subdivision into extractions gives its mean age and so may differ significantly from the age of under- or overlying deposits (Braitseva et al. 1993). In some cases uncharred wood can be redeposited by a debris avalanche and yield older ages. Stratigraphic relationships of tephra and debris avalanche layers help to reduce ^{14}C dating uncertainty. Ages of debris avalanche deposits are given in Fig. 6 and in the text in ^{14}C years BP. Radiocarbon ages were converted to calendar years using the procedure of Stuiver and Reimer (1993) in order to calculate time intervals between debris avalanche formation (Fig. 7; Table 3).

Prehistoric debris avalanches and related eruptions

Figure 2 shows the area where deposits older than the KL ash from Kliuchevskoi Volcano (5800–6000 years BP; Table 1) were studied. In this area no Holocene debris avalanche deposit older than the KL ash was observed. If one exists, it would have to be confined to the western sector of the southern slope or have covered only a small area. Two layers of coarse fragmented deposits underlie Holocene soil and pyroclastic cover near the Semkorok extrusive domes (Figs. 3, 6), but their lithology suggests that they represent the agglomerate mantle of the domes.

The oldest of the known Holocene debris avalanches (I) forms a tongue of hummocky debris southeast of the volcano and extends as far as 15 km from

Table 2 Radiocarbon dates for the debris avalanche deposits

Date (years BP)	Laboratory number	Extraction[a]	Description of the material	Location (river valley)
530 ± 80	GIN-7411		Charcoal in pyroclastic flow deposits	Kamenskaya
540 ± 70	IVAN-395	I + II + III	Carbonized soil	Suhoi Il'chinets
1130 ± 110	GIN-7415	I	Soil	Kamenskaya
1130 ± 80	IVAN-212	I	Soil	Kabeku
1120 ± 50	IVAN-247		Charcoal in pyroclastic flow deposits	Suhoi Il'chinets
1630 ± 50	IVAN-246		Charcoal in pyroclastic flow deposits	Suhoi Il'chinets
1940 ± 70	IVAN-264	I	Carbonized soil	Baidarnaya
2970 ± 80	GIN-7836	I	Soil	Kabeku
3200 ± 320	GIN-7836	II		
3100 ± 70	GIN-8810	II	Carbonized soil	Suhoi Il'chinets
3760 ± 100	GIN-7400	I	Soil	Mutny
3710 ± 140	GIN-7845	I + II	Soil	Kabeku
3950 ± 130	IVAN-236	I	Carbonized soil	Kabeku
3980 ± 100	IVAN-236	II		
3960 ± 40	GIN-7850	I	Soil	Kabeku
5550 ± 100	GIN-7812	I	Soil	Mutny
5570 ± 40	GIN-7813	I	Soil	Mutny
5570 ± 60	IVAN-219		Buried wood in debris avalanche I deposits	Kabeku
6420 ± 140	IVAN-219			

NOTE: The dates with GIN code were obtained in the Geological Institute, Moscow; the dates with IVAN code, in the Institute of Volcanology, Petropavlovsk-Kamchatsky.

[a] Numbers of successive alkaline extractions from soil samples

Table 3 Ages and parameters of the Holocene debris avalanches at Shiveluch volcano

Debris avalanche	Rounded ^{14}C ages (years BP)	Calendar years	Maximum runout (L), km	Maximum observed thickness (m)	Area (km^2)	Volume (km^3)	Associated pyroclastic deposits observed	Presence of synchronous landslide deposits in Mutny River section
XIV		AD1964	16	20	98	~2	a, b, c	+
XIII	500	AD1430	20	15	>200	>3	a, b, c	−
XII	1100	AD970	18	20	>100	~2	a, b, c	+
XI	1450	AD630	7	40	5	<1	−	+
X	1500	AD600	19	10	<100	~1	a, b, c	−
IX	1700	AD380	9	40	?	?	c	−
VIII	1850	AD150–190	9	6	?	?	a, c	−
VII	1900	AD120	14.5	10	<100	<1	b, c	+
VI	2550	BC780	11	8	<100	<1	a, b, c	+
V	3100	BC1330	11	15	<100	~1	a, c	+
IV	3700	BC2080	14	> 8	?	?	a, b, c	
III	4000	BC2490	>10	>10	?	?	a, c	
II	5500	BC4350	14	2	?	?	a, c	
I	5700	BC4530	15	12	?	?	a, b, c	

NOTE: a – pumice fall, b – pyroclastic flow, c – surge. The minus sign means absence of the landslide; blank indicates that deposits of this age are not exposed in the section

the modern crater (Figs. 3, 4). It is 10–12 m thick in sections at Kabeku River near its margin. The deposits are composed of typical block facies (Glicken 1986), with individual fragments of dominantly light-gray andesite up to 2 m across. The matrix consists of coarse pink sand with lenses of greenish sand. The deposits contain some pumice lapilli and are overlain by a pumiceous surge deposit up to 2 m thick and minor pumice-fall deposits, which suggest that a moderate eruption of juvenile material followed the debris avalanche. In Suhoi Il'chinets Valley this eruption deposited pyroclastic surges with occasional angular rock fragments of various lithology (Fig. 6). In other valleys deposits related to this eruption have not been found. In the lower Kamenskaya River this debris avalanche deposit was supposedly identified near the outer edge of avalanche X one. The area and volume of avalanche-I deposit cannot be determined but seem at least as large as those of the 1964 eruption (Fig. 3).

In the Kabeku Valley the lower part of this avalanche deposit contains uncharred wood dated at 5570 and 6420 ^{14}C years BP (Table 2). At the same time dates of 5550–5570 years were obtained much higher in the overall stratigraphic section (Fig. 6). The deposit rests directly on thick paleosoil which includes the ash from the initial eruptions of Kliuchevskoi Volcano

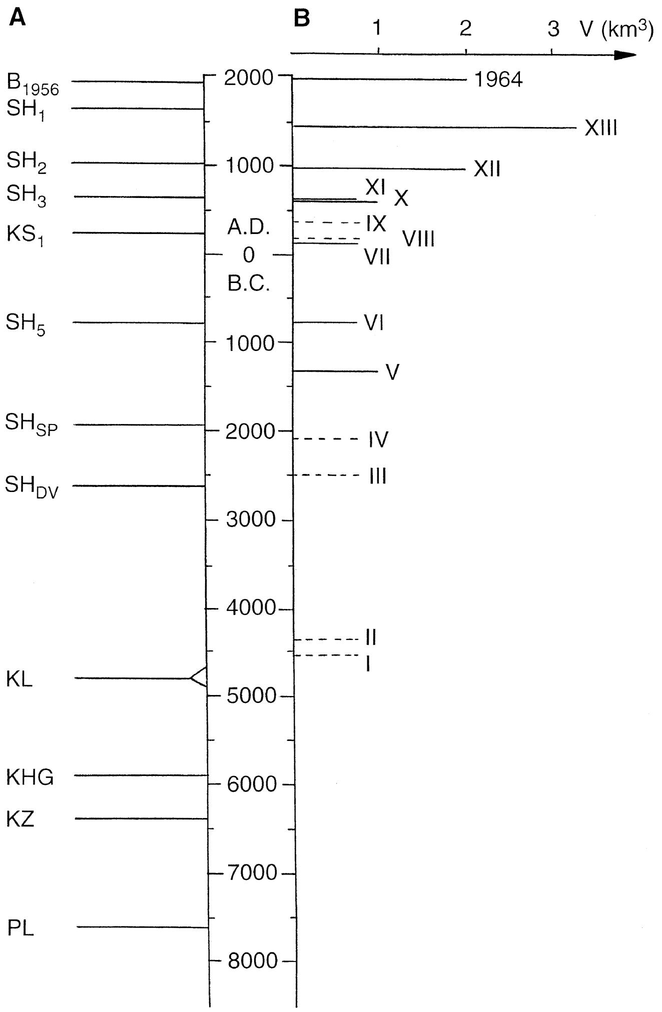

Fig. 7 Chronology of debris avalanche events (*B*) on a calendar scale and their positions with respect to marker ash layers (*A*). *V* volume of the debris avalanche deposits; *dashed lines* show assumed volumes. Numbers of the debris avalanches as in Figs. 3 and 6; for codes of marker ash layers see Table 1 and Fig. 6

(KL; Fig. 6; Table 1) dated at 5800–6000 ^{14}C years BP (Braitseva et al. 1995). Thus, the age of the avalanche can be roughly estimated at approximately 5700 ^{14}C years BP. The thickness of paleosoil suggests that the debris avalanche was preceded by a long period of relative quiescence of the volcano.

The next avalanche (II), also exposed along Kabeku River, is up to 2 m thick 13 km from the crater (Fig. 4). Its deposits are composed of light-colored andesite fragments supported by a pinkish sandy matrix. Down the Kabeku Valley a transition takes place to a subunit of more thoroughly mixed muddy material. The debris avalanche is immediately overlain by a 0.6-m-thick pyroclastic surge deposit. In sections along Suhoi Il'chinets River, the deposits of this eruption consist of surges with occasional debris of various lithologies. In the valley of Mutny River (Figs. 2, 6), deposits supposedly of the same eruption are represented by minor pumice fall. The maximum runout of the avalanche in the Kabeku Valley is approximately 13 km from the modern eruptive center; consequently, its area and volume are similar to those of the 1964 deposit. Debris avalanche II overlies avalanche I and is overlain by the SHdv marker ash layer (Fig. 6). These stratigraphic relations and ^{14}C dating suggest that this debris avalanche formed approximately 5500 ^{14}C years BP.

The deposits of debris avalanche III are exposed only in the Suhoi Il'chinets Valley approximately 10 km from the crater, where they are more than 10 m thick (Fig. 6). They underlie pumice-fall deposits of the same eruption. In the Kabeku Valley the deposits of this eruption consist of minor pumice fall and surge deposits, but correlations suggest that the fall deposits reach a maximum thickness north of Shiveluch along First Lednikovyi creek (Figs. 6, 8A). The area and volume of this avalanche deposit could be approximately half those of the 1964 one. The debris avalanche overlies the SHdv marker ash layer and underlies deposits of an eruption related to the next debris avalanche, IV. Stratigraphic position and ^{14}C dates yield an age for debris avalanche III of approximately 4000 ^{14}C years BP.

Deposits of debris avalanche IV crop out only in the Kabeku Valley, where they are more than 8 m thick approximately 13 km from the vent and pinch out at 14 km. The debris avalanche deposit is overlain by 3 m of pyroclastic flow and surge deposits, which contain both light-colored andesitic pumice and black basaltic andesitic scoria with white bands. The deposits of this eruption are pumice fall and surge in the Suhoi Il'chinets Valley, surge on the slopes of Old Shiveluch in the southwest sector, and pumice fallout in the Karina, Mutny, and First Lednikovyi valleys (Fig. 6). The age of avalanche IV is approximately 3700 ^{14}C years BP. This avalanche is of particular interest, because it may have opened the vent for the following eruption of high-potassium–high-magnesium basaltic ash (SHsp), unusual for Shiveluch, approximately 3600 ^{14}C years BP (Volynets et al. 1997).

Debris avalanche V was first identified at the bottom of the section along Baidarnaya River (Figs. 2, 3) where it forms a clast-supported, fines-poor deposit more than 3 m thick with lower contact not exposed. Typical debris avalanche deposits more than 3 m thick at the same stratigraphic position were documented in Suhoi Il'chinets Valley (Figs. 2, 3). In both valleys the debris avalanche deposits are directly overlain by pyroclastic surge deposits, which occur also in sections along Karina and Kabeku rivers (Fig. 6). The runout of this avalanche in the southern sector was at least 11 km. The age of the avalanche is approximately 3100 ^{14}C years BP. A clast-supported deposit more than 3 m thick (lower contact not exposed) also crops out at a similar stratigraphic position in the upper reach of Mutny Valley. The deposit consists of large subrounded fragments and is very similar to the Baidarnaya deposit. In the same valley a small landslide deposit from a crater on the high slope of Old Shiveluch was also found. All the deposits described in this paragraph have simi-

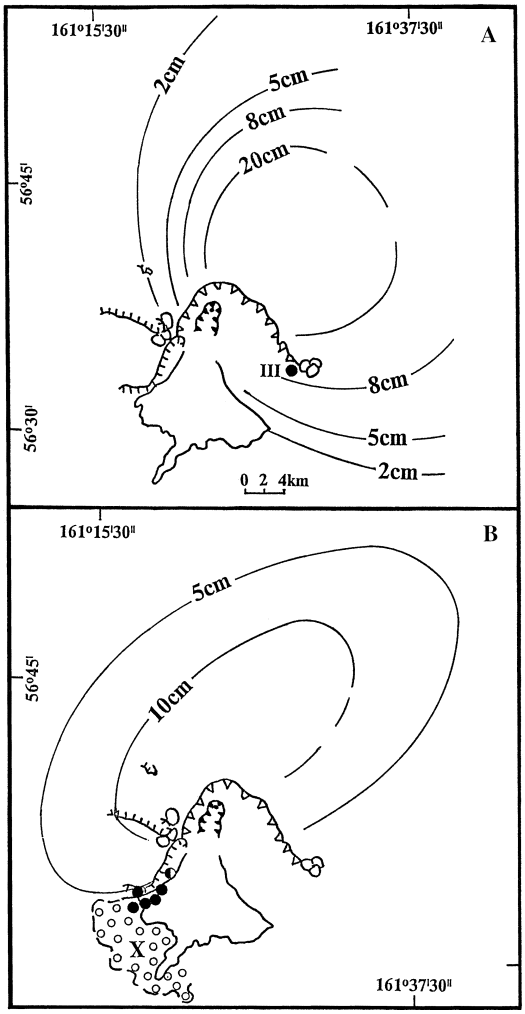

Fig. 8 Maps showing the deposits of some eruptions related to flank failure events: *A* eruption ~4000 ^{14}C years BP; *B* ~1500 ^{14}C years BP. Isopachs for tephra fallout are given. *Circles* show the sections where debris avalanche deposits (*solid circles*) and pyroclastic flow deposits (*open circles*) are present. The outline of the 1964 debris avalanche deposits is given for comparison

lar stratigraphic position (Fig. 6) and might have resulted from the same volcano-tectonic event or separate events closely spaced in time.

Debris avalanche VI is exposed in Baidarnaya and Kabeku valleys at distances of 9.5 and 11 km, respectively, from the volcano. In Kabeku the margin of this avalanche can be observed, but in Baidarnaya the avalanche can be observed only in one section and does not crop out farther from the volcano. The minimum travel distance is therefore 11 km. The deposit of avalanche VI displays typical block facies. Juvenile deposits of the eruption include a 25-m-thick pyroclastic flow deposit underlain by surge deposits in Baidarnaya Valley, thin surge deposits in Kabeku Valley, and pumice fall in Karina, First Lednikovyi, and Mutny valleys (Fig. 6). Ashfall from this eruption forms a marker ash layer named SH_5 with a radiocarbon age of approximately 2550 years BP (Braitseva et al. 1997a), which gives us the approximate age for avalanche VI as well.

Debris avalanches VII–XII

Debris avalanches VII–XII form a cluster, separated from each other only by 30- to 340-year intervals (Fig. 7). This cluster coincides in time with general intensification of Shiveluch activity, especially between 1800 and 1400 ^{14}C years BP, as suggested by multiple pumice-fall layers between the SH_3 and KS_1 marker ash layers north of the volcano.

The debris avalanche-VII deposits, first found on the western slopes of Old Shiveluch (Fig. 3), were associated with the Karan domes. They are easy to distinguish on the air photos and have a typical hummocky topography. Travel distance of the avalanche in this sector is approximately 14.5 km, with a volume of approximately 1 km^3. Deposits exposed in a roadcut near the outer edge of the avalanche show a reddish matrix embedded in which angular andesitic fragments up to 25 cm across are scattered. The landslide formed a large horseshoe-shaped crater in the upper reach of Karina River, destroying several extrusive domes formed prior to the eruption. This event also caused lahars and likely triggered a small landslide in Mutny Valley and the eruption of pyroclastic surges. The deposits of the western slopes probably correlate to the debris avalanche and overlying pyroclastic-flow deposits in Kabeku Valley, 9 km from the modern crater (Figs. 3, 6). The thin layer of small multi-colored debris from this avalanche also occurs in sections along Suhoi Il'chinets River interlayered with surge deposits (Fig. 6). The avalanche events on the western and southern slopes might have occurred simultaneously or closely in time. Debris avalanche VII formed approximately 1900 ^{14}C years BP, as suggested by its stratigraphic position between the SH_5 and KS_1 marker ash layers and the date of 1940±70 ^{14}C years BP from under it. Pyroclastic-flow deposits in Kabeku and Baidarnaya valleys, and surge deposits in other valleys, represent the juvenile products of this avalanche-related eruption.

Debris avalanche VIII (Figs. 3, 7) was formed a few decades after avalanche VII. Both deposits can be observed in the same outcrop in the Kabeku Valley 9 km from the vent, which is the maximum travel distance for avalanche VIII. The juvenile components of the eruption include minor surge and fall deposits exposed in all the valleys. The stratigraphic position of the avalanche-VIII deposit, between the KS_1 marker ash layer and debris avalanche-VII deposit dated at approximately 1900 ^{14}C years (Fig. 6), suggests an age of approximately 1850 ^{14}C years BP.

The deposit of debris avalanche IX is exposed no more than 9 km from the vent and only in Suhoi Il'chinets Valley. Here, near its outer edge, it is approximately 40 m thick and consists of several units of block facies material interbedded with sand-rich subunits. Associated juvenile deposits were likely formed by a pyroclastic surge. The age of this avalanche is estimated at approximately 1700 ^{14}C years BP, as it overlies the KS_1 marker ash layer with an age of 1800 ^{14}C years BP and underlies a soil horizon and pyroclastic flow deposit that contains charcoal dated at 1630±50 years BP (Fig. 6).

The margins of debris avalanches X–XIII are well seen on air photos beyond the area covered by the 1964 avalanche deposits. The deposit of debris avalanche X occurs only in the southwest sector. In Baidarnaya Valley it is approximately 2 m thick, 9 km from the crater, and can be traced downstream to a distance of 12.5 km. In Kamenskaya it crops out down the valley to its terminus at approximately 19 km and consists of dark gray and reddish rock fragments. Avalanche X is overlain by surge, flow, and fall deposits. The fall deposits are dirty-yellow pumice lapilli with abundant lithic clasts spread west and north of the volcano (Fig. 8B). The age of the eruption can be estimated at approximately 1500 ^{14}C years, as its deposits are bracketed between the SH_3 and KS_1 marker ash layers, with ^{14}C ages of approximately 1400 and 1800 years, respectively, and are underlain by the soil and pyroclastic flow deposit containing charcoal dated at 1630±50 ^{14}C years BP (Fig. 6).

We observed, in section, folded soil and pyroclastic cover immediately beyond the edge of the avalanche-X deposit in Kamenskaya Valley. Individual fall beds are broken into pieces and shifted or rotated by 90°, suggesting that avalanche X pushed and disturbed them. Such interaction between avalanche and underlying deposits was reported by Siebe et al. (1992) at Jocotitlan Volcano (Mexico) and also was observed for the 1964 eruption of Shiveluch (see below). Marker ash horizons within the folded sequence, which overlies an older avalanche, are still recognizable and include the Shdv layer, so we can assume that the lower unit is avalanche I or II.

A 40-m-thick landslide breccia crops out on the western slopes of the volcano in Karina Valley, approximately 5.5 km from the modern Karan domes. This deposit lies between the dirty-yellow pumice lapilli described previously and the SH_3 marker ash layer. The upper 3 m of this unit resemble the typical matrix-supported reddish debris avalanche deposits and is interpreted as debris avalanche XI. Downward the debris continuously changes to gray and dark-gray, clast-supported material with subrounded clasts up to 4 m across and only a small amount of light-gray matrix. Approximately 2 km farther downstream the deposits are finer grained but still clast supported. Avalanche XI is clearly visible on the air photos. Its travel distance is approximately 7 km and area approximately 5 km^2, and its volume is an estimated 0.2 km^3. It probably came from a crater carved into the most recent Karan dome, which formed in the time between avalanches VII and XI. This event was also recorded by a landslide in Mutny Valley (Fig. 6). Avalanches X and XI occur only west and southwest of the edifice and are separated by only a very short time, probably a few decades. Thus, we suggest that both might be associated with activity of a vent on the western slope rather than in the central crater.

Debris avalanche XII was deposited in a broad area south of the vent (Fig. 3) and was one of the most voluminous of the avalanches. The thickness of the deposit exceeds 20 m in Baidarnaya and Kamenskaya valleys and along the upper reaches of Kabeku Valley, and more than 8 m in Suhoi Il'chinets Valley. It is clast supported with minor amounts of a light reddish-pink sandy matrix. In the upper part of Kabeku Valley two subunits of the typical avalanche deposits were found separated by a sandy subunit 1 m thick. Avalanche XII traveled approximately 18 km, covers an area of 120 km^2, and has a volume of approximately 2 km^3. The maximum thickness as well as the maximum runout are both in the southwest sector (Fig. 3). The following eruption produced mainly pyroclastic flows and surges and minor fallout. The surge deposits can be observed in all sectors around the volcano (Fig. 6). The eruption took place approximately 1100 ^{14}C years BP, as estimated from the position of its deposits between the SH_2 and SH_3 marker ash layers and additional ^{14}C dates (Fig. 6; Table 2). Debris avalanche XII was the last in the time cluster of similar events described above.

Debris avalanche XIII occurred 500 years later (Fig. 7) and produced the most voluminous deposit, well exposed in Baidarnaya, Kamenskaya, and Kabeku valleys (Figs. 3, 6). It is composed of gray, gray-pinkish, and dark-gray clast-supported material. In outcrops on the left bank of Kabeku River, near the margin of the avalanche, a continuously thinning "tail" of dry mottled small debris can be observed. The avalanche traveled up to 20 km, covers more than 200 km^2, and has a volume of more than 3 km^3. Its surface is hummocky, although it is almost everywhere smoothed by flow and fall deposits of the same and later eruptions. The succeeding plinian eruption produced dominantly pyroclastic flows and only moderate fallout (Fig. 9A). The age of the eruption is approximately 500 ^{14}C years BP (1430 AD calendar age, according to the technique of Stuiver and Reimer 1993). This eruption is likely responsible for the form of the pre-1964 crater.

The 1964 eruption

The eruption of 12 November 1964, and its deposits, were described in many papers (Piip and Marhinin 1965; Tokarev 1964, 1967; Gorshkov and Dubik 1970; Bogoyavlenskaya et al. 1985; Belousov 1995; Firstov 1996; Sheridan 1996). We add some details based on our field observations and analysis of air photos.

The eruption was preceded by a period of varying seismic activity beginning in January 1964 (Tokarev

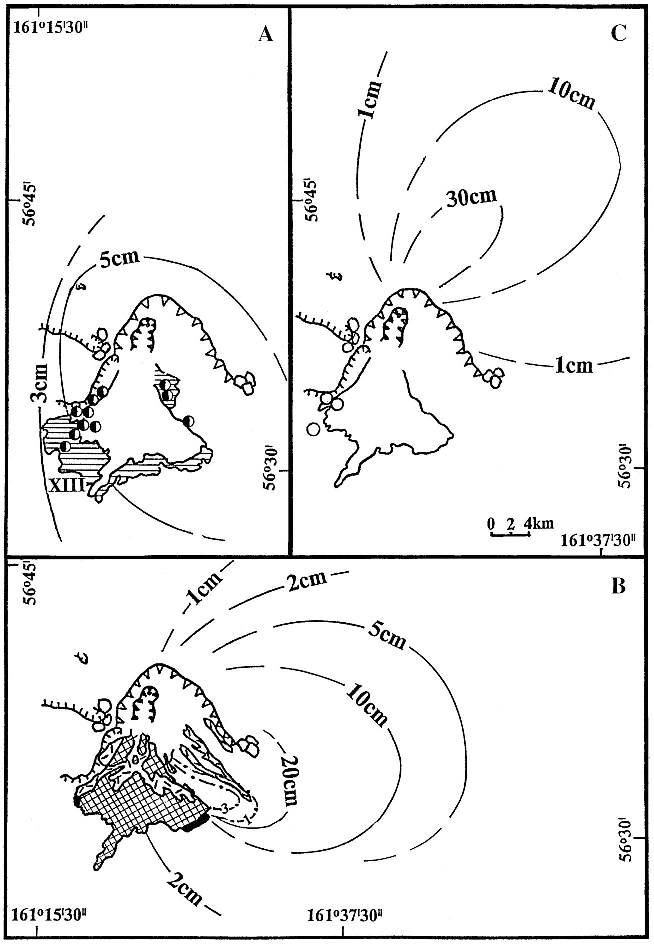

Fig. 9A–C Maps showing the deposits of some eruptions related to flank failure events. **A** ~500 ^{14}C years BP (1430 AD); **B** 1964 AD; **C** 1854 AD. In **B** *solid isopachs* are for pumice fallout, *dashed isopachs* are for the ash of the initial eruption; disturbed older deposits near the front of the debris avalanche are shown in *black*. For other designations see Fig. 8

1964, 1967). The climactic stage of the eruption included the destruction of the volcano's summit by flank failure (Belousov 1995), subsequent phreatic explosion (Belousov 1995), and a powerful plinian eruption resulting in pyroclastic fall and flows (Gorshkov and Dubik 1970). The deposits include a "resurgent agglomerate" (debris avalanche), with an area of 98 km^2 and a volume of approximately 1.5 km^3, that covered the southern slope of the volcano (Gorshkov and Dubik 1970), an olive-gray phreatic ash rich in accretionary lapilli (Belousov 1995), a plinian fall dispersed mainly southeastward, and a pyroclastic flow, most of which was deposited south of the volcano with a minor flow in Mutny Valley as well (Piip and Marhinin 1965; Gorshkov and Dubik 1970). The new crater almost perfectly coincides with the pre-1964 one, which suggests that it was the domes built in the old crater that were mainly involved in failure (Gorshkov and Dubik 1970).

The 1964 avalanche deposit, as well as the newly formed crater, were described in detail by Gorshkov and Dubik (1970): a large horseshoe-shaped crater, hummocky surface of the deposits, obvious signs of material movement down the slope (narrow ridges up to 20 m high, oriented radially to the eruptive center, and "shadow zones" behind older hills), huge rockslide megablocks that formed "stairs" up to 150 m high adjacent to the crater, large blocks crushed into small clasts but retaining "the mutual arrangement of separate pieces," etc. The deposit was reported to be cold and inert 10 days after the eruption and contained blocks of frozen debris that later melted and formed hummocks. The composition of the clasts corresponds to that of the destroyed domes. The forest remained untouched just beyond the outer edge of the avalanche (Fig. 10).

Interpretation of air photos allowed the recognition of two types of topography of the debris avalanche deposit, which overlap in the south and southeast sectors (Fig. 11). This suggests that the rockslide deposits were emplaced in two successive stages, similar to the three-stage emplacement of the Mount St. Helens avalanche (Voight et al. 1981). Gorshkov and Dubik (1970) wrote that the newly formed crater had a compound structure and consisted of two parts (Fig. 9B): the southern part open to the south that is larger (area of ca. 4 km^2) than the northern part (ca. 1 km across). The first rockslide may have formed the southern part of the crater, the above-described "stairs" (Fig. 12), and the major part of the avalanche. This rockslide corresponds to the strongest earthquake registered at 7:07:20 a.m. (Tokarev 1967). The topography of this part of the avalanche can be examined in the southwest sector, where it resembles the surface of a lava flow (Fig. 11A). It is net-like: In some places flows or tongues several hundred meters wide and 1–2 km long are crossed by transverse narrow ridges 2–15 m high consisting of grouped conical hummocks and short ridges. The transverse ridges are separated by narrow crack-like valleys. This portion of the avalanche looks massive; its thickness near the outer edge is 3–5 m. Large blocks of froz-

Fig. 10 Forest refuge near the southwest margin of the 1964 debris avalanche deposits, Baidarnaya River. (Courtesy L. D. Sulerzhitsky; photo taken in summer 1965)

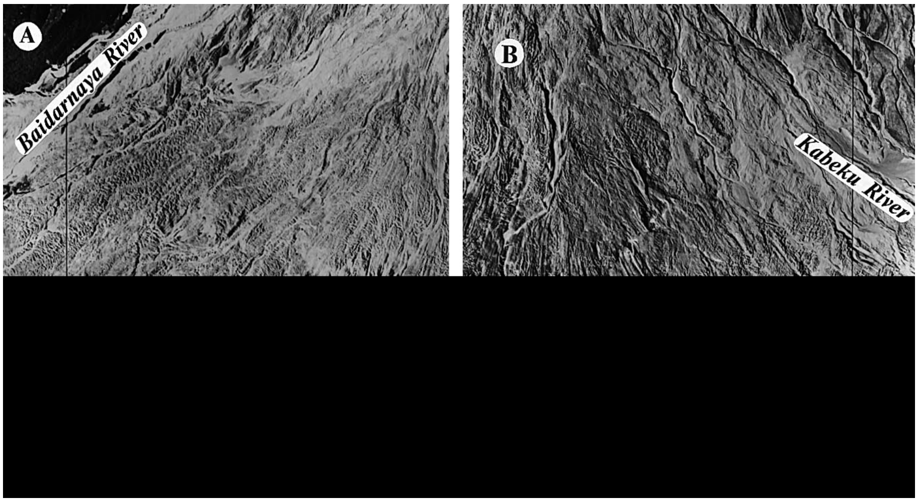

Fig. 11A, B Photos showing the two types of 1964 avalanche morphology. **A** first portion, southwest margin; **B** second portion, southeast margin

en debris were thrown beyond the frontal edge of the avalanche. When they melted, they formed isolated conical hummocks that now can be seen up to 2.5 km from the edge of the avalanche. These blocks, as well as large rock fragments, impacted into the older deposits (L. D. Sulerzhitsky, pers. commun.) and indicate the abrupt stop of the mass movement. They resemble features described by Siebe et al. (1992) at Jocotitlan Volcano. The drop height (H) of the first portion of the avalanche was approximately 1.8 km (calculated according to Siebert 1996), the runout (L) 13 km, and the H/L 0.14.

The failure of the southern part of the edifice might have provoked the next, smaller rockslide, which was recorded by the second strong earthquake at 7:13:40 a.m. Ascending magma might also have helped to displace and destroy the extrusive domes, as before the climactic eruption of Bezymianny in 1956 (Gorshkov 1959). This second avalanche was emplaced on top of the first. Its topography is dominated by radially spaced narrow ridges, which sometimes form fan-like structures especially in the southeast sector (Fig. 11B). These ridges are broken by transverse rupture zones. The morphology indicates a higher velocity for the second avalanche. It had bigger drop height of approximately 2.4 km, a runout of approximately 16 km, and an H/L of 0.15.

Surge deposits occur between the avalanche and overlying flow deposits but have not yet been studied. For example, in Baidarnaya Valley we found a deposit approximately 1 m thick directly overlying the 1964 avalanche and underlying pyroclastic flow deposits. It consists of stratified dark-gray small lithic clasts (1–2 mm in diameter), is poor in fines, and contains scattered pumice lapilli. Similar beds have been observed in deposits from several other Shiveluch eruptions and might indicate directed blasts that occurred due to slide-induced pressure reduction on shallow cryptodomes. Ash similar to the 1964 olive-gray phreatic ash (Belousov 1995) occurs among products of other

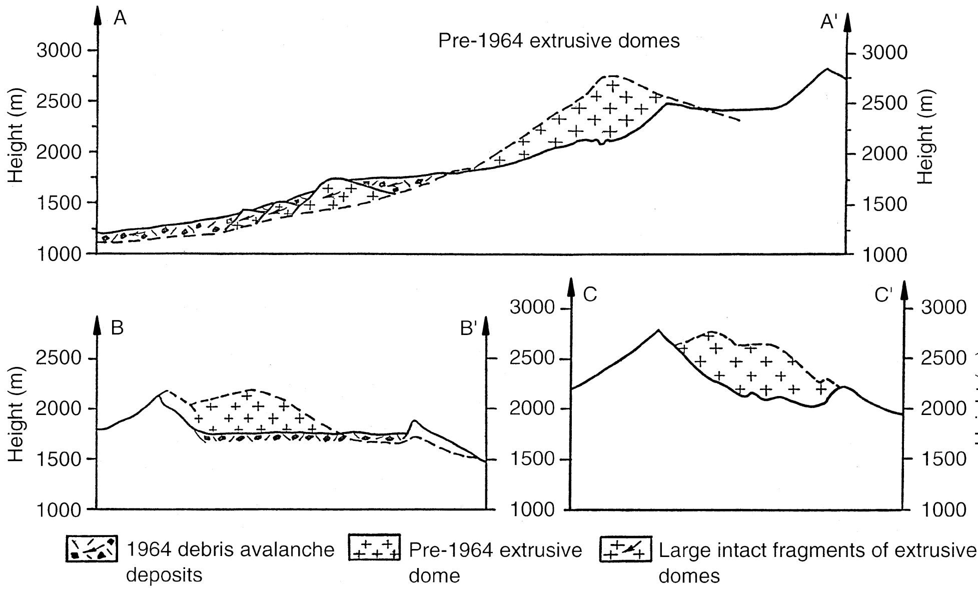

Fig. 12 Profiles showing pre-1964 (*dashed line*) and post-1964 (*solid line*) morphology of the Young Shiveluch eruptive center. Locations of the profile lines shown in Fig. 3

eruptions, some of which directly followed the formation of debris avalanches. This ash also needs further examination.

The area of the newly formed crater is approximately 5.2 km^2, and the volume of domes involved in the rockslide, approximately 1.5–1.8 km^3. The volume of the avalanche is believed to be larger, approximately 2 km^3, due to dilation during emplacement. The mean thickness of the avalanche deposit is approximately 20 m, and the maximum thickness, 100–200 m (Fig. 12).

Gorshkov and Dubik (1970) mentioned that the frontal part of the avalanche moved over the surface, scraping off loose pumice deposits. In the southeast sector the 2-km-long margin of the avalanche deposit is edged by a prominent zone of folded terrain approximately 500 m wide. The folds bear inclined but still standing dead trees. The folded terrain is composed of material belonging to avalanche XIII, which formed approximately 1430 AD, overlain by the SH_1 marker ash layer. Apparently, this material was horizontally pushed by the 1964 avalanche, but farther downslope the same deposits retain their original hummocky topography and are covered with live forest. Unfortunately, the contact between the 1964 avalanche and underlying units is not well exposed, and it is difficult to tell how many of them were folded. A small patch of similar folded terrain was also observed in Kamenskaya Valley. Here the contrast between folded and untouched deposits is even more prominent. The forest-covered, ideally smooth SH_1 pyroclastic flow deposit near the edge of the 1964 avalanche is folded and transformed into high hummocks, carrying broken dead trees, that look very much like the frontal part of an older avalanche. Similar disturbance of the underlying surface by the avalanche was described previously in this paper for avalanche X and is believed to resemble the folding and thrust faulting of soft sediments caused by the Jocotitlan debris avalanche (Siebe et al. 1992).

In an outcrop along a tributary of Kamenskaya River we found pieces of a small wooden volcanological station, which had been located approximately 7 km south of the crater and was destroyed during the 1964 erupion (Gorshkov and Dubik 1970). The wood is buried in the lower part of the 1964 avalanche deposit and traveled approximately 3 km from its original place. A small landslide overlying the B_{1956} marker ash and covered by surge deposits of the 1964 eruption was noted in the section in Mutny Valley (Fig. 6) and is likely a result of the 1964 eruption.

We refined the dispersal pattern for both phreatic and plinian fall deposits of the 1964 eruption (Fig. 9B). The 1964 lahars apparently originated from pyroclastic flows rather than from the debris avalanche itself (first noticed by Gorshkov and Dubik 1970), as they are confined only to the valleys containing pyroclastic flow deposits. Besides the lahars described previously for the southern sector of the volcano, we also found lahar deposits in Mutny Valley 12 km from the crater rim.

The problem of the 1854 debris avalanche

We did not find the deposits derived from the 1854 failure of the volcano's summit, reported by Gorshkov and Dubik (1970) and Belousov (1995) based on the historical record. Perhaps the avalanche traveled less than 8 km and therefore is not present in our sections. Nonetheless, it is useful to analyze the 500 years of Shiveluch eruptive history between debris avalanches XIII (1430 AD) and XIV (1964 AD) in order both to consider the problem of the 1854 eruption and to look for long-term precursors for the 1964 event. A detailed description of all these eruptions will be published elsewhere, and here we only intend to correlate the depositional record with the historical evidence (Fig. 13).

During the ~200 years that followed the 1430 AD eruption, only one minor pumice fall was recorded in the southeast sector of the volcano, no more than 11 km from the vent. Approximately 1650 AD a very strong eruption (SH_1) produced fallout, voluminous pyroclastic flows more than 23 km long, and accompanying surges. The historical record of Shiveluch eruptions begins in 1739, but Gorshkov and Dubik (1970) doubted the certainty of these reports and thought that Shiveluch had been silent during the eighteenth and the

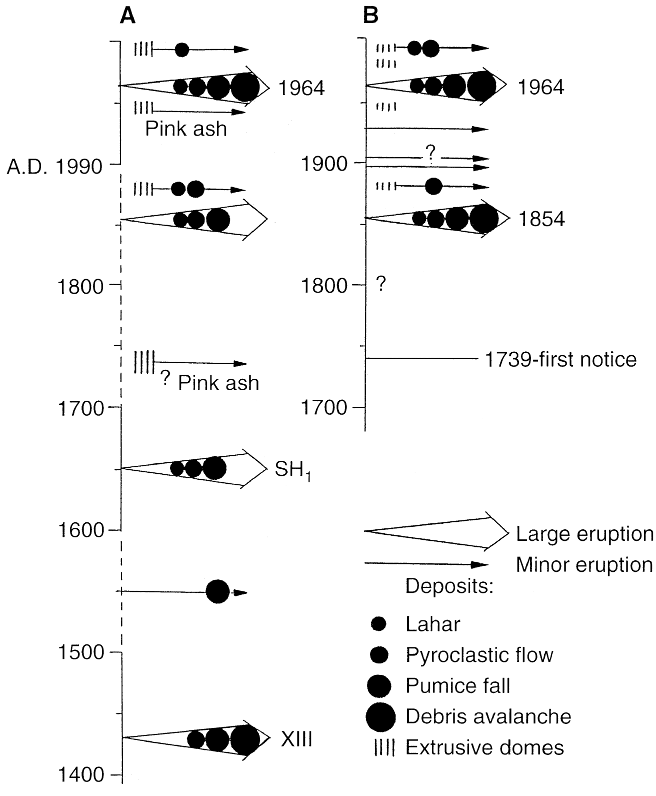

Fig. 13 **A** Depositional and **B** historical records of Shiveluch activity during the past 600 calendar years. In **A** the deposits are recorded more than 8 km from the crater. Breaks in the time scale in **A** show uncertainty of dating for some eruptions. The position of the eruptions in these breaks is supported by the stratigraphic position of their deposits. See text for explanation

first half of the nineteenth centuries. The first reliable report is for a strong eruption in 1854. Gorshkov and Dubik (1970) and Meniailov (1955) summarized the descriptions of the 1854 eruption, based mostly on observations by residents. They described: (a) increased fumarolic activity on the northern side of Shiveluch during October-December 1853; (b) the failure of the summit of the volcano during the night of February 17–18; (c) extensive lava flows on all the slopes of the volcano reaching Elovka River in the west; (d) the destruction of forest at the foot of the volcano by enormous stones and the breaking of ice on Elovka and Kamchatka rivers; and (e) an ash fall in Kliuchi (~45 km south of the volcano, up to 30.5 cm thick on snow) and Tigil' (~200 km northwest of the volcano). Even if some observations are not correct, the 1854 eruption nevertheless seems to have been powerful.

The depositional record shows only one significant eruption between SH_1 and 1964 (Fig. 13). On the southern slope the record contains pyroclastic flow deposits extending no farther than 15 km, surge deposits, thin lenses of white fine ash, and very extensive lahar deposits traceable down all the valleys on both the southern and western slopes. No traces of the ash are preserved in the Kliuchi section today, and Gorshkov and Dubik (1970) misinterpreted the SH_1 layer in this section to be the 1854 ash. They made the same mistake with the SH_1 pyroclastic flows on the southern slopes of the volcano. On the northern slope the deposits of only one strong eruption were recorded for this stratigraphic interval. They are represented by an extensive white pumice fall with a dispersal axis toward the northeast (Fig. 9C), as well as by surge deposits. Fall deposits are 30–40 cm thick on the edge of the modern glacier in the Second Lednikovyi Valley, 11 km from the eruptive center; the thickness is similar to that of the 1964 fall at the same distance downwind (Fig. 9B). We are inclined to correlate the above-described deposits to the 1854 eruption. The effects of this eruption, reported by witnesses, seem to be similar to those of the reconstructed one; the eruption was strong, the boulders that destroyed the forest and broke ice on the rivers were derived from extensive lahars, and the evidence of ash fall in Tigil' coincides in general with the reconstructed area of ash dispersal.

The discrepancies between the depositional and historical records can be explained in the following way: The reported outpouring of lava was previously disproved by Bogdanovitch (1904). Gorshkov and Dubik (1970) pointed out that the natives could have mistaken pyroclastic and mud flows for lava flows, as they did in 1956 while watching the Bezymianny eruption. The reported thickness of fresh ash in Kliuchi (1 foot, reported as 1′, or 30.5 cm) seems unreal and puzzled us for many years until I. V. Melekestsev assumed that it was due to a misprint in the original report by Ditmar (1890) and that Ditmar meant to report 1′′ (1 inch, or 2.54 cm) and not 1′ (30.5 cm). This inference is supported by the report of Hertz (cited in Meniailov 1955) on the ash dispersal mainly northward and the original thickness of ash in Kliuchi of approximately 3 cm. The last number seems reasonable, since a blanket of fine ash of such thickness, covering thick winter snow, could easily be destroyed during snow storms and melting.

Although the historical record includes a large failure of the volcano summit in 1854, we found no debris avalanche deposit of this age 8 km or more from the volcano. If any debris avalanche was emplaced, it must have been very small compared with the other documented deposits. The folded deposits forming a festoon apron at the southeast edge of the 1964 avalanche, and a small patch in Kamenskaya Valley, were taken for the 1854 debris avalanche deposits by earlier researchers (Gorshkov and Dubik 1970; Belousov 1995), but in fact they consist of folded SH_1 pyroclastic flow deposit (~1650 AD) in the southwest and of deformed avalanche-XIII deposits (~1430 AD) covered by the SH_1 ash layer in the southeast sectors. Accordingly, the large pre-1964 crater, previously thought be a result of the 1854 eruption (Gorshkov and Dubik 1970; Belousov 1995), actually formed earlier, most likely in 1430 AD, due to the avalanche-XIII emplacement.

Between the SH_1 and 1854 deposits only one layer of fine dark-pink ash is recorded in all sectors (Fig. 13), probably related to contemporaneous extrusive dome growth based on its similarity to ash of the 1944–1950 domes. This ash has not been dated, but the thickness of sandy loam between it and the SH_1 layer suggests an interval not less than 50 years. The eruption of this pink ash could therefore be either the last prehistoric one or the first recorded (with some uncertainty) in 1739 or 1790–1810 (Gorshkov and Dubik 1970). The largest eruption between 1854 and 1944 occurred in 1879–1883 and apparently included formation of an extrusive dome and an explosion with pyroclastic flow eruption (Gorshkov and Dubik 1970). This coincides with our finding of a small pyroclastic flow deposit and extensive lahars within this stratigraphic interval (Fig. 13). Other historical eruptions (1897–1898, 1905, 1928–1929) were weak, and their traces might be found only nearer the volcano. The 1964 collapse was preceded by four episodes of extrusive dome growth during 1944–1950, each studied in detail (Piip 1948; Meniailov 1955; Gorshkov and Dubik 1970). Dome formation was accompanied by minor explosive activity and incandescent avalanches that traveled up to 4 km. The deposits of these eruptions are confined to within 8 km of the crater, where they are represented by 1–2 thin layers of fine dark-pink ash. Both the depositional and historical record suggest that most of the domes that filled the 1430 AD crater were emplaced in several eruptive episodes somewhat after the SH_1 eruption, during the eighteenth to twentieth centuries (Fig. 13). Therefore, the material of the 1964 debris avalanche consisted mostly of these fragmented domes. Analyzing the historical eruptive activity of Shiveluch, Gorshkov and Dubik (1970) supposed that the next eruption after 1964 would take place between 1980 and 1995 and consist of dome formation. This forecast came true exactly in 1980, when a new extrusive dome began to grow in the 1964 crater.

Discussion

The deposits of at least 14 Holocene debris avalanches, including that of 1964, occur at the foot of Shiveluch Volcano. Most avalanches covered the southern sector of the volcano, but two avalanches occurred on the western slope of Old Shiveluch (Fig. 4). Figure 7 shows a chronology of the Shiveluch debris avalanches during the Holocene. Radiocarbon ages of debris avalanches and marker ash layers have been converted to calendar years according to the technique of Stuiver and Reimer (1993) in order to estimate real durations between avalanches (Tables 1, 3). The first large Holocene avalanches formed approximately 4530–4350 BC. Since ~ 2490 BC, at least 13 avalanches formed over intervals of 30–900 years. Six large avalanches were closely spaced between 120 and 970 AD, with recurrence intervals of ~30–340 years. Some of the avalanche deposits on the southern slopes (e.g., X) are narrow (Fig. 3), whereas those of avalanches V, VI, and XII were confined by the Old Shiveluch caldera rim and occupy sectors approximately 80° wide. Maximum runout for the Holocene avalanches is estimated at ~20 km. Debris avalanches V, VI, VII, XI, XII, and XIV (1964) likely correlate to small landslides in the Mutny Valley (Fig. 6).

All the avalanches are dry and contain no significant amount of clay. Most of the lahars associated with these eruptions seem to originate not from debris avalanches themselves but from later pyroclastic flows. Interaction with the underlying surface varies from gliding over to eroding the surface and may cause folding of older deposits in front of the avalanche. Some avalanche deposits display definite stratification or overlapping topography that might indicate multistage emplacement. A subunit of thoroughly mixed material, which underlies most of the avalanche deposits, indicates fragmentation of clasts due to the interaction with the underlying surface; such interaction also allows incorporation of pumice from the underlying deposits. All avalanches but one (XI) were followed by magmatic eruptions, which resulted in the emplacement of pyroclastic fall, flow, and surge deposits (Table 3). Features of some surge deposits suggest an origin from directed blasts triggered by rockslides; they need further examination. Debris avalanches XIII and XIV were followed by minor phreatic eruptions. Shiveluch offers a rare opportunity to study debris avalanches of various scales. Features derived from the interaction with the underlying surface, associated pyroclastic deposits, avalanche-triggered directed blast deposits and other surge deposits require further study.

Rockslides were followed mainly by moderate plinian eruptions, whereas the largest plinian eruptions, such as those producing SH_1, SH_2, or SH_3 (Braitseva et al. 1997b), were not associated with avalanches (Fig. 7). The 1964 rockslide obviously occurred due to preceding dome formation and involved these domes. The prehistoric failures are also believed to have occurred due to preceding extrusive dome growth, both in the Young Shiveluch crater and on the western slopes of Old Shiveluch. Consequently, the general reason for avalanche formation might be a high magma supply rate and the repetitive dome formation. The avalanche deposits found on the western slope indicate that traditional hazard zoning only for the southern slope must be revised, as Karina and Mutny valleys are also exposed to debris avalanche and pyroclastic flow hazards.

Acknowledgements The research described in this paper was partially supported by grants from the Russian Foundation for Basic Research and National Science and Technology Program "Global Environmental and Climatic Change". We are very grateful to O. Braitseva who took part in field work in 1978 and shared her field data. We thank L. Sulerzhitsky, who took part in G. S. Gorshkov's expedition to Shiveluch in 1965 and provided his photos taken in 1965 and 1978 as well as valuable suggestions. L. Siebert and Ph. Kyle read the first version of the manuscript and made helpful comments. We are very grateful to D. Swanson and an anonymous reviewer whose detailed comments and suggestions greatly improved the manuscript.

References

Beget JE, Kienle J (1992) Cyclic formation of debris avalanches at mount St Augustine volcano. Nature 356:701–704

Belousov AB (1995) The Shiveluch volcanic eruption of 12 November 1964:explosive eruption provoked by failure of the edifice. J Volcanol Geotherm Res 66:357–365

Belousova MG, Belousov AB (1994) Repetitive, magma driven, large scale edifice failures of Shiveluch Volcano (Kamchatka). Abstracts of the IAVCEI General Assembly, Ankara, Turkey

Bogdanowitsch K (1904) Geologische Skizze von Kamtschatka. Peterm Geogr Mitt., H. 3, Gotha

Bogoyavlenskaya GE, Braitseva OA, Melekestsev IV, Kirianov VYu, Miller CD (1985) Catastrophic eruptions of the directed blast type at Mount St. Helens, Bezymyanny and Shiveluch volcanoes. J Geodyn 3:189–218

Braitseva OA, Litasova SN, Sulerzhitsky LD (1992) Validity of radiocarbon dating in regions of active volcanism in Kamchatka. Quarternary Int 13 (14): 143–146

Braitseva OA, Sulerzhitsky LD, Litasova SN, Melekestsev IV, Ponomareva VV (1993) Radiocarbon dating and tephrochronology in Kamchatka. Radiocarbon 35 (3): 463–476

Braitseva OA, Melekestsev IV, Ponomareva VV, Sulerzhitsky LD (1995) The ages of calderas, large explosive craters and active volcanoes in the Kuril-Kamchatka region, Russia. Bull Volcanol 57 (6): 383–402

Braitseva OA, Melekestsev IV, Ponomareva VV, Kirianov VYu (1996) The caldera-forming eruption of Ksudach Volcano about cal. AD 240, the greatest explosive event of our era in Kamchatka. J Volcanol Geotherm Res 70 (1–2): 49–66

Braitseva OA, Ponomareva VV, Sulerzhitsky LD, Melekestsev IV, Bailey J (1997a) Holocene key-marker tephra layers in Kamchatka, Russia. Quaternary Res 47 (2): 125–139

Braitseva OA, Sulerzhitsky LD, Ponomareva VV, Melekestsev IV (1997b) Geochronology of the greatest Holocene explosive eruptions in Kamchatka and their imprint on the Greenland glacier shield. Trans (Doklady) Russian Acad Sci Earth Sci Sect 352 (1): 138–140

Ditmar K (1890) Reisen und Aufenthalt in Kamtschatka in den Jahren 1851–1855. Th. 1. Beitrage zur Kenntniss des Russischen Reiches. Bd. 7, Spb

Dvigalo VN (1984) Growth of the dome in the crater of Shiveluch Volcano in 1980–1981 according to photogrammetric data. Volcanol Seismol 2:104–109 (in Russian)

Francis PW, Wells GL (1988) Landsat Thematic Mapper observations of debris avalanche deposits in the Central Andes. Bull Volcanol 50:258–278

Firstov PP (1996) Reconstruction of the time history for the catastrophic Shiveluch eruption of November 12, 1964 based on data relating to wave disturbances in the atmosphere and volcanic tremor. Volcanol Seismol 18:415–432

Glicken H (1986) Rockslide-debris avalanche of May 18, 1980, Mount St. Helens Volcano, Washington. PhD dissertation, The University of California, Santa Barbara, 303 pp

Gorelchik VI, Garbuzova VT, Droznin DV, Levina VI, Firstov PP, Chubarova OS, Shirokov VA (1995) The Shiveluch Volcano: deep structure and prediction of eruptions using detailed seismicity data, 1962–1994. Volcanol Seismol 17:423–448

Gorshkov GS (1959) Gigantic eruption of the volcano Bezymianny. Bull Volcanol 20:77–109

Gorshkov GS, Dubik YuM (1970) Gigantic directed blast at Shiveluch Volcano (Kamchatka). Bull Volcanol 34:261–288

Khubunaya SA, Zharinov NA, Muravyev YaD, Ivanov VV, Boloyavlenskaya GE, Novgorodtseva TYu, Demyanchuk YuV, Budnikov VA, Fazlullin SM (1995) 1993 eruption of Shiveluch Volcano. Volcanol Seismol 17:1–20

Melekestsev IV, Braitseva OA (1984) Gigantic rockslide avalanches on volcanoes. Volcanol Seismol 4:14–23 (English translation in Volcanol Seismol 6:495–508, 1988)

Melekestsev IV, Dirksen OV (1997) A large amphitheater and debris avalanche at Bakening Volcano (Kamchatka, Russia). IAVCEI General Assembly, Abstracts, p. 96

Melekestsev IV, Braitseva OA, Ponomareva VV (1990) Holocene activity dynamics of Mutnovskii and Gorelyi volcanos and the volcanic risk for adjacent areas (as indicated by tephrochronology studies). Volcanol Seismol 9 (3): 337–362

Melekestsev IV, Volynets ON, Ermakov VA, Kirsanova TP, Masurenkov YuP (1991) Shiveluch Volcano. In: Fedotov SA, Masurenkov YuP (eds) Active volcanoes of Kamchatka, vol 1. Nauka, Moscow, pp 84–92 (in Russian, summary in English)

Meniailov AA (1955) Shiveluch Volcano: geological structure, composition of products and eruptions. Trans Laboratory of Volcanology, USSR Academy of Sciences, no. 9, 265 pp (in Russian)

Moore JG, Normark WR, Holcomb RT (1994) Giant Hawaiian landslides. Annu Rev Earth Planet Sci 22:119–144

Palmer BA, Alloway BV, Neall VE (1991) Volcanic-debris-avalanche deposits in New Zealand: lithofacies organization in unconfined, wet-avalanche flows. In: Fisher RV, Smith GA (eds) Sedimentation in volcanic settings. SEPM Spec Publ 45:89–98

Pevzner MM, Ponomareva VV, Melekestsev IV (1998) Cherny Yar: reference section of the Holocene marker ash layers for the NE coast of Kamchatka. Volcanol Seismol 19:389–406

Piip BI (1948) A new eruptive state of Shiveluch Volcano from the end of 1944 to May, 1945, and information on its geologic structure and past eruptions. Bull Volcanol Observatory Kamchatka 14:38–51 (in Russian)

Piip BI, Marhinin EK (1965) Gigantic eruption of Shiveluch Volcano on November 12, 1964 (preliminary report). Bull Volcanol St 39:3–28 (in Russian)

Ponomareva VV, Pevzner MM (1994) Large debris avalanches in the eruptive history of Shiveluch Volcano, Kamchatka, Russia. Abstracts of the IAVCEI General Assembly, Ankara, Turkey

Ponomareva VV, Pevzner MM (1995). Large flank failures in the Holocene eruptive history of Shiveluch Volcano, Kamchatka, Russia. Abstracts of the XXI General Assembly of the International Union of Geodesy and Geophysics (IUGG), Boulder, Colorado, p. A 458

Ponomareva VV, Pevzner MM (1996) Predicting explosive eruptions from the eruptive history reconstruction (Shiveluch Volcano, Kamchatka, Russia, case study) Ann Geophys 14 (Suppl 1): C118 (Abstracts of the EGS XXI General Assembly, The Hague)

Sheridan M (1996) Shiveluch 1964 debris deposit: intermediate type between volcanic debris avalanche and block- and ash flow. Ann Geophys 14 (Suppl 1): C 118 (Abstracts of the EGS XXI General Assembly, The Hague)

Siebe C, Komorowski J-C, Sheridan MF (1992) Morphology and emplacement of an unusual debris-avalanche deposit at Jocotitlan Volcano, Central Mexico. Bull Volcanol 54:573–589

Siebert L (1984) Large volcanic debris avalanches: characteristics of source areas, deposits, and associated eruptions. J Volcanol Geotherm Res 22:163–197

Siebert L (1996) Hazards of large volcanic debris avalanches and associated eruptive phenomena. In: Scarpa R, Tilling RI (eds) Monitoring and mitigation of volcano hazards. Springer, Berlin Heidelberg New York, pp 541–572

Stuiver M, Reimer PJ (1993) Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35:215–230

Tokarev PI (1964) The swarm of earthquakes at Shiveluch Volcano in May 1964. Bull Volcano St 38 (in Russian)

Tokarev PI (1967) Gigantic eruption of Shiveluch Volcano on November 12, 1964 and its precursors. Proc Russ Acad Sci Phys Earth 9:11–22

Ui T, Yamamoto H, Suzuki K (1986) Characterization of debris avalanche deposits in Japan. J Volcanol Geotherm Res 29:231–243

Voight B, Glicken H, Janda RJ, Douglass PM (1981) Catastrophic rockslide avalanche of May 18. In: Lipman PW, Mullineaux DR (eds) The 1980 eruptions of Mount St. Helens, Washington. US Geol Surv Prof Pap 1250:347–378

Volynets ON, Ponomareva VV, Babansky AD (1997) Magnesian basalts of Shiveluch andesite volcano, Kamchatka. Petrology 5 (2): 183–196

Zharinov NA, Bogoyavlenskaya GE, Khubunaya SA, Demyanchuk YuV (1995) A new eruption cycle of Shiveluch volcano, 1980–1993. Volcanol Seismol 17:21–30