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A Giant Landslide–Explosion Cirque and a Debris Avalanche at Bakening Volcano, Kamchatka

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This study revealed that the giant cirque of Bakening Volcano had been produced by its eruption ca. 8000–8500 carbon-14 year ago. The eruption is supposed to have been heralded by a large earthquake ($M > 7$) resulting in the collapse and slide of the SE sector of the cone. The landslide unroofed the hydrothermal system and triggered an explosion which was followed by an ash-and-block pyroclastic flow. A rockslide avalanche rolled down into the valley of the Srednyaya Avacha River and travelled as far as 10–11 km along it. The avalanche deposited its debris material over an area of 18–20 km^2 measuring 0.4-0.5 km^3 in volume. These deposits dammed the river, produced two lakes (Bezymyannoe and Verkhneavacha), and gave birth to a large lahar which traveled along the valley much farther.

Bakening Volcano (53°54′N, 158°04′E), rising to a height of 2277.7 m above sea level, is located at the upper reaches of the Srednyaya Avacha River. This volcano and a huge trough (Figs 1 and 2) on its SE slope have long since attracted the attention of volcanologists. As far back as 1851–1854 K. Ditmar [9] visited Bakening during his stay in Kamchatka. In his book he emphasized the high destruction of its cone, especially in the east and southeast. B. I. Piip [20] called this negative landform a "broad and deep barranco (caldera valley)". A. E. Svyatlovsky [1], [21] examined the air photographs taken during the 1946 aerial survey of Kamchatkan volcanoes and called this landform a "deep rocky cleft" that cut the SE slope of the cone from the destroyed edge of the crater to its foot. None of these researchers, however, described this landform comprehensively or explained its origin.

The first volcanologist who did this was A. I. Tsurupa [22] in 1978. He described this landform in detail and evaluated its size (1.5×2.2 km) and volume (0.308 km^3). He wrote

[22, p. 72]: "From the caldera mouth[a] to the Sr. Avacha River I did not find any deposits whose composition or form might be indicative of their origin as a result of a landslide or a lateral blast". On this basis he classified this landform as an "erosion caldera".

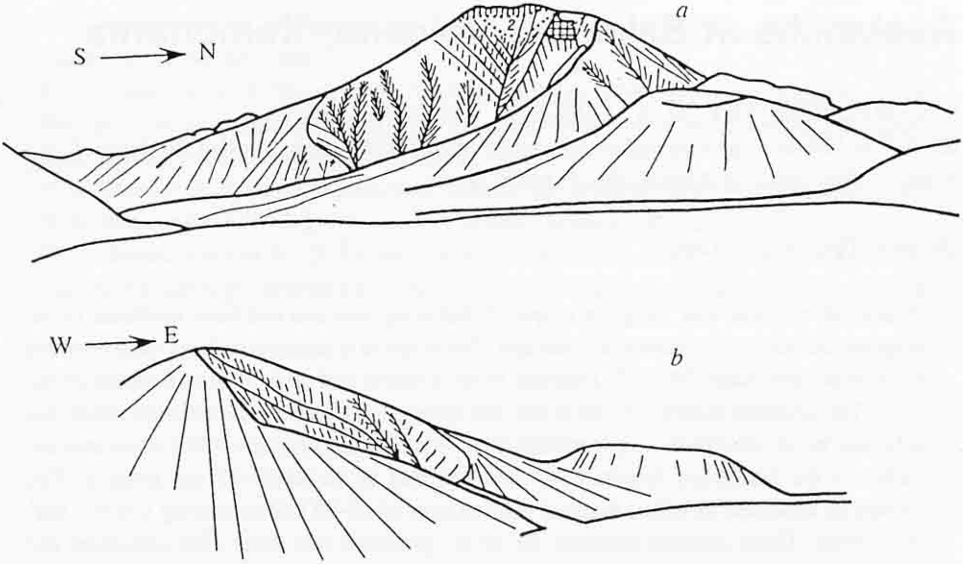

Figure 1 General view of Bakening Volcano [22]: *a* – view from the east, *b* – view from the south.

Our special-purpose survey at Bakening during the summer of 1995 enabled us to form a radically different notion of the origin of this landform and determine its age. At the present time the trough is an oval-shaped negative feature measuring 2.9×1.35 km, which is a catchment basin of a creek that flows to the Sr. Avacha River. Its maximum depth from the reconstructed initial surface of the cone to the creek's waterline is 250 m (Fig. 3). Using a topographic map of 1:50 000, we estimated the present day volume of the hollow to be ~ 0.37 km^3.

Outside of the volcano's edifice the NE bank of the creek flowing from this basin is an almost continuous cliff, > 1.5 km long and 60–70 m high. The deposits exposed in this cliff have a two-member structure.

The upper 50–60 m of the cliff are made up of a coarse clastic material of light gray and beige to light gray color containing a large amount of rock fragments included in a

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[a] We believe the term "caldera mouth" to be a poor choice.

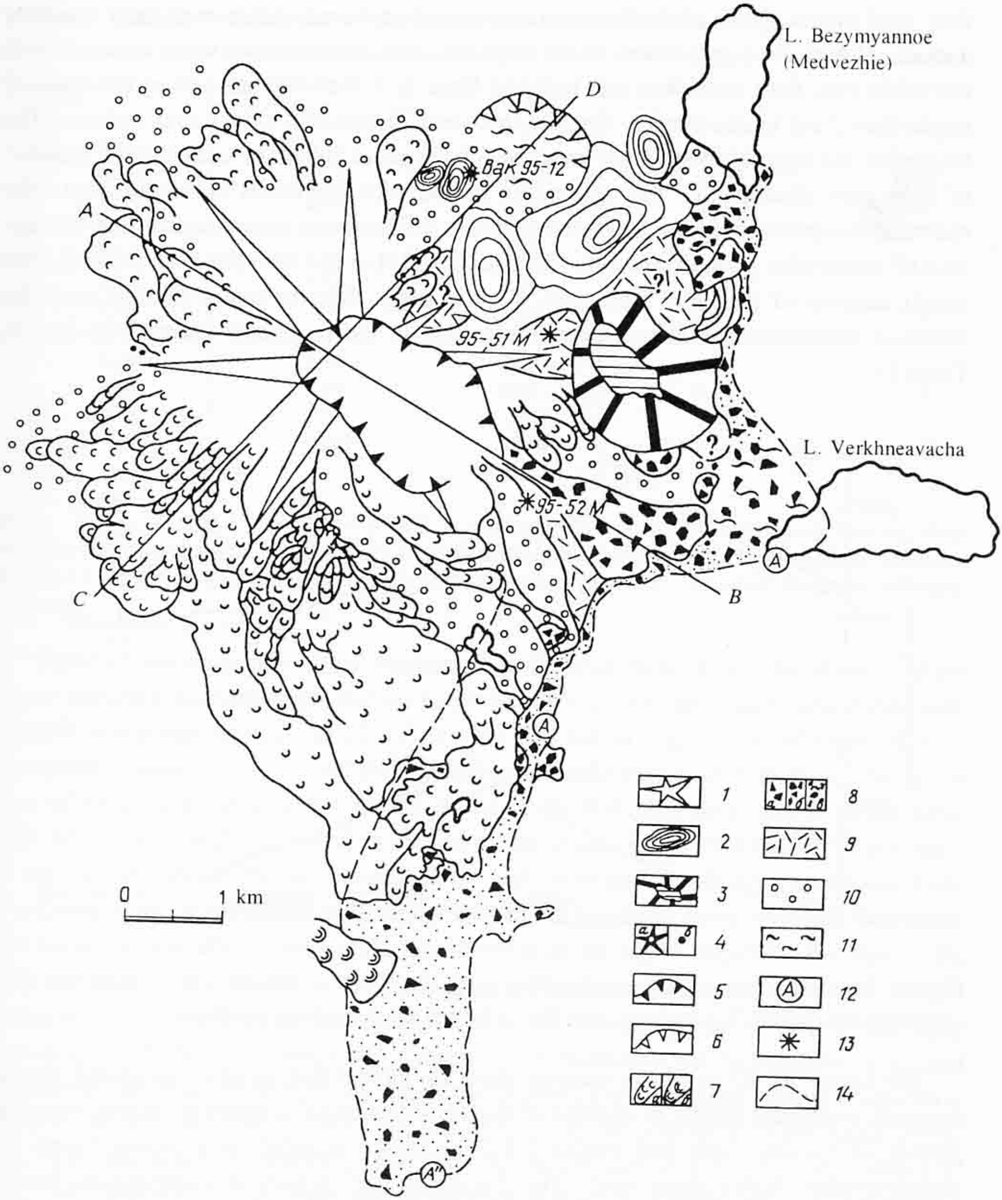


Figure 2 Schematic geological and geomorphological map of the Bakening area: *1* – stratovolcanic cone; *2* – lava dome; *3* – tuya; *4* – cinder and lava cones (*a* – shown in map scale, *b* – not to scale); *5* – rim of cirque; *6* – rim of maar scarp; *7* – lava flows of Bakening (*a*) and other eruptive centers (*b*); *8* – debris avalanche deposits (*a* – well preserved, *b* – reworked by rivers, *c* – reworked by lakes); *9* – pyroclastic flow deposits; *10* – proluvial plains and alluvial fans; *11* – lake beds; *12* – section description site (see Fig. 6); *13* sample site and number; *14* – inferred area of debris avalanche propagation.

dust–sand matrix. Most of the fragments consist of unaltered, dense or slightly vesicular andesite of dark dove-gray color. These fragments look homogeneous when observed with the naked eye, their maximum size being as large as 1.5 m. The amount of the material larger than 2 cm in size ranges, visually, between 20 and 40% of the rock volume. The fragments are slightly rounded or knocked off. Some of them are enclosed in "jackets" of light gray aleuropelite. The amount of altered rock fragments is insignificant. The chemical composition of the fragments is fairly uniform and approximates that of calc-alkalic, moderately potassic andesite (Samples 95-52M-A and 95-52M-B in Table 1). The matrix consists of gray and light gray, slightly dusty, fine- to coarse-grained sand. Its chemical composition is little different from that of the fragments (Sample 95-52A in Table 1).

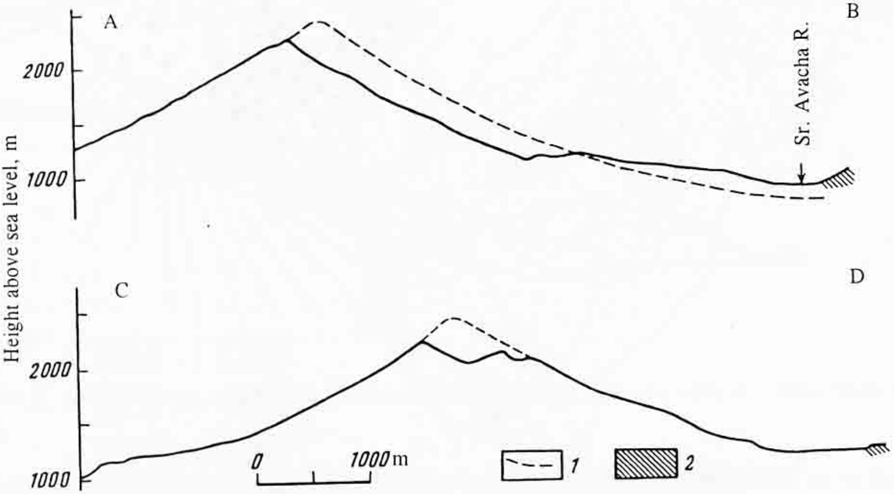


Figure 3 Hypsometric profiles across Bakening cone: AB – SW–NE; BC – NW–SE; *1* – reconstructed surface; 2 – bedrock. See Fig. 2 for the location of the profiles.

The lower 10–20 m of the outcrop show an unstratified member of coarse clastic deposits, consisting mostly of angular or slightly knocked-off fragments ranging between gravels of varying sizes and blocks 1.5–2 m across included in a brown matrix of inequigranular, highly dusty sand. The fragments vary greatly in composition: lavas, volcanic breccias from the near-vent segment of the cone and a large amount of altered rocks. The base of the sequence is not exposed over the entire cliff. The floor of the Sr. Avacha Valley is covered by blocks from this sequence (without the fine material of the matrix, which had been washed away by water).

In our opinion, these two sequences were paragenetically related to the origin of this trough and provide a key for understanding the mechanism of its formation.

Table 1 Chemical compositions of pyroclastic flow deposits and lava dome.

Oxide	95-52M-A	95-52M-B	95306/4	95-12
SiO_2	63,05	61,61	64,46	64,28
TiO_2	0,73	0,72	0,62	0,52
Al_2O_3	15,99	16,40	15,74	17,02
Fe_2O_3	2,16	3,05	2,27	1,62
FeO	2,39	2,38	2,56	1,95
MnO	0,08	0,09	0,07	0,1
MgO	1,64	2,08	1,90	1,13
CaO	5,74	5,54	5,26	3,88
Na_2O	4,26	4,18	3,81	4,79
K_2O	2,30	2,08	2,08	2,1
P_2O_5	0,04	0,02	0,11	0,24
LOI	1,22	1,34	0,99	–
Total	99,60	99,49	99,87	97,63

Note. Sample 95-52M-A – matrix (< 2 mm) of pyroclastic flow; 95-52M-B – fragments from that flow; 95306/4 – tephra collected at a distance of 3 km from the volcano (analyzed at Geological Institute, Moscow): Bak-95-12 – lava dome on NE slope of Bakening (collected and analyzed by F. Dorendorf, Hettingen University, Germany).

Based on our observations and interpretation of aerial photographs, the material of the lower sequence had been deposited on an uneven hilly (or hill-and-ridge) topography with relative elevations as large as 10–15 m. One can see in Fig. 2 that localities of hilly topography occur on an inclined plain of intricate configuration (in map view), the major part of which is situated within the SE sector of the Bakening foot, that is, in the same area where the trough concerned is located on the slope. These localities occur presently at the eastern side of the Sr. Avacha River and between Lake Bezymyannoe and Lake Verkhneavacha. However the hilly topography of the preserved lower sequence fragments are buried almost ubiquitously under the deposits of the upper sequence, the tops of the hills rising but a few meters above the surface of the latter. Because the deposits of both sequences are severely eroded, it is difficult to reconstruct the details of the hilly topography of the lower sequence. Generally, it resembles the topography of typical explosion, landslide–explosion, and landslide deposits that were produced by eruptions at Bandai-san Volcano (Japan, 1888) [3], [19], [30], [33], Bezymyannyi (Kamchatka, 1956) [3], [33], Shiveluch (Kamchatka, 1964) [3], [8], and Mount St. Helens (USA, 1980) [2], [3], [34], and also by landslides and avalanches at Kamen (Kamchatka) [16] and Ontake (Japan) [29].

We did not find any indications of hiatus or erosion in the zone of contact between the upper and lower sequences. This means that the lower sequence was covered by the material of the upper member almost immediately after the deposition of the former. Evidence supporting the absence of any notable difference in their ages is the similar structure of the soil–pyroclastic cover draping the tops of both sequences.

As follows from our reconstruction, apart from the Bakening foot, the deposits of the lower sequence covered wholly the floor and partially the sides of the Sr. River Valley over its segment of 11–12 km up to the present-day ~ 500-meter water level of the river's channel. This is indicated, in particular, by the abundance, of the valley's floor, of huge boulders and blocks of Bakening volcanics (up to 1.5–2 m across) that were left there after the washout of the lower sequence. The total area covered by the material of the lower sequence might have been as large as 18–20 km^2, its volume being 0.4–0.5 km^3. Some difference between the volume of the hollow (~0.37 km^3) and that of the clastic material of the sequence can be explained by the extra clastic material scoured from the sides and floor of the valley during transportation [29] and by the loosening of the cone's rocks during their disintegration.

On the contrary, the primary surface of the upper coarse-clastic sequence inclined toward the Sr. Avacha Valley (from 12–10° above to 2–3° below) does not show any large topographic highs. The main microrelief forms are small ridges, wavy in plan and arranged parallel to the slope, and the lows separating them. The elevations of the ridge crests above the floors of the lows measure a few meters. This kind of wavy microrelief in volcanic areas is generally common to volcanogenic proluvial and lahar plains [11], [12], [13], [14], [15], [35], and also to pyroclastic flows [6], [8], [28], [31]. However, the volcanogenic proluvial genesis of the upper sequence is ruled out through the absence of any traces of the material reworking by temporary streams: there is no sorting or rounding of the fragments and no bedding. The lahar genesis of the sequence is ruled out by the too uniform composition of the fragments, the evidence uncharacteristic of lahars [11], [14].

The particle-size analysis of the matrix (< 2 mm) in the upper sequence revealed that this material was very similar to the matrix of the pyroclastic flows from Bezymyannyi (Figs 4 and 5; Table 2). The composition of the Bakening samples (Fig. 4) is intermediate between the compositions of the juvenile vesicular andesite pyroclastic flows of the catastrophic and most of the noncatastrophic eruptions of Bezymyannyi (Fig. 4), on the one hand, and bears a close resemblance to the composition of the ash-and-block pyroclastic flow produced by the July 30, 1985, eruption of Bezymyannyi, on the other. The particle-size statistical data of the Bakening coarse-clastic deposits of the upper sequence are almost identical with those of the Bezymyannyi pyroclastic deposits (Table 2).

Therefore, proceeding from the whole set of data (macro- and microrelief features, the relatively uniform assemblage of fragments, the andesitic composition of the material, the type of the matrix, etc.), the deposits of the upper sequence can be classified with sufficient certainty as the material of a block-and-ash flow [2], [28], [31]. The pyroclastic flows of this type usually accompany the growth of extrusive viscous-lava domes, like, e.g., the Novyi dome which grew in the crater of Bezymyannyi after its famous 1956 eruption [6], [7].

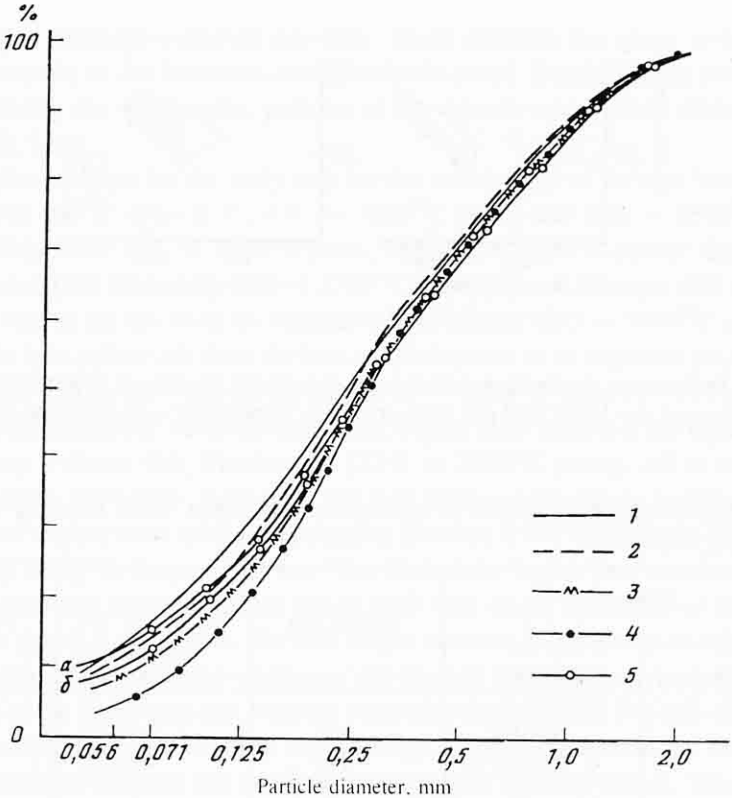


Figure 4 Cumulative particle-size curves for pyroclastic-flow deposits of Bezymyannyi (*1–4*) and Bakening (*5*): *1* – juvenile vesicular andesite pyroclastic flow of the 1956 eruption (average of nine samples); *2*, *3* – block-and-ash flows of the 1984–1989 eruptions (average of 28 samples) and of the 30 July 1985 eruption, respectively; *4* – juvenile vesicular andesite pyroclastic flow of the 1984–1986 eruptions (average of 24 samples); *5* – Bakening pyroclastic flow (*a* – Sample 95-52M, *b* – Sample 95-51M). See Fig. 2 for sample sites.

Apart from the "main" pyroclastic flow described above, we discovered another similar flow of the same age, isolated from the "main" one and containing a larger amount of resurgent material, in a small creek valley in the NE sector of the Bakening foot.

It should be mentioned that we found a thin tephra unit deposited by the same eruption in soil–pyroclastic sections outside of this pyroclastic flow. This tephra material consists of bombs with a maximum size-varying uniform gravel (max. size of 1 cm) and coarse-grained sand of gray dense and slightly vesicular, coarsely crystalline andesites.

More problematic is the origin of the lower coarse-clastic sequence. There are two alternatives here: either these are landslide or explosion–landslide deposits. The fact is that using the present-day criteria, it is very difficult to distinguish between these formations even for well-known historical eruptions. Naturally, it is much more difficult to classify deposits of these types having a prehistoric age, like in the case discussed.

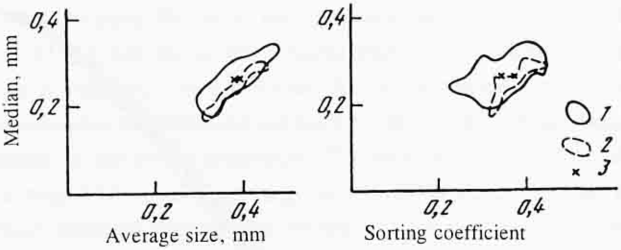


Figure 5 Particle size comparison between the pyroclastic deposits of Bezymyannyi (*1*, *2* – pyroclastic flows of the 1984–1989 and 1956 eruptions, respectively) and Bakening (*3*).

Table 2 Particle-size characteristics of pyroclastic-flow matrix from Bakening (1, 2) and Bezymyannyi (3–6).

Sample no.		Median, mm	Average size, mm	Sorting index
Serial no.	Field no.			
1	95-51M	0,26	0,39	0,38
2	95-52M-A	0,26	0,38	0,35
3	2BK85	0,26	0,37	0,33
4	"P-G"P	0,26	0,38	0,33
5	"Yu"P	0,25	0,38	0,35
6	B56	0,24	0,38	0,37

Note. 1, 2 – pyroclastic flow, see Fig. 1 for sample sites; 3, 4 – block-and-ash flows of July 30, 1985 and 1984–1989 (average of 28 samples); 5, 6 – juvenile pyroclastic flows of the 1984–1989 (average of 24 samples) and 1956 (average of 9 samples) eruptions, respectively.

In so far as we do not have direct evidence for attributing the material of the lower coarse-clastic sequence to landslide or landslide–explosive deposits, we have to rely on indirect data helpful for refining our knowledge of its origin: (1) the paragenetic relations of the lower sequence with the pyroclastic flow deposits of the upper sequence; (2) the finding of a subsynchronous tephra unit; (3) the recent preceding eruptive history of the volcano (see below). Relying on these data, we can conclude that first the volcano continued to be potentially active, even though there were no eruptions, before the deposition of the lower coarse-clastic sequence, and, secondly, the event concerned was accompanied by explosive activity. These arguments allow us to accept, with greater certainty, the alternative of the landslide–explosive genesis of the sequence.

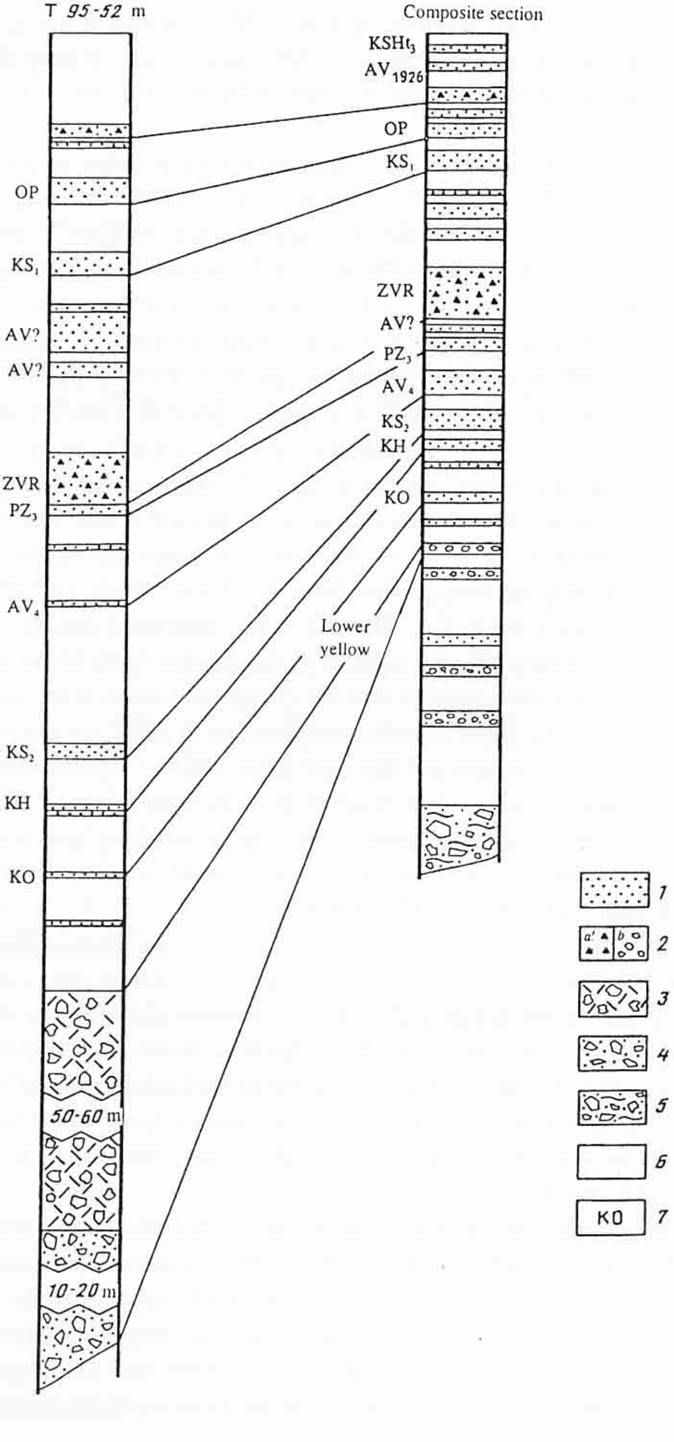
Unfortunately, we did not find layers with organic matter above or below the sequence of plant remains, suitable for radiocarbon dating, inside it. For this reason we dated this event using a tephrachronological approach. Much attention was given to compiling a composite section of the Holocene soil–pyroclastic cover, locating tephra markers in it, and determining the stratigraphic position of the deposits under study relative to these markers [5], [26].

The tephra markers for the study area are the transit ashes of Avacha Volcano (1926 eruption [18] 600^{14}C years B.P., $AV_1 \approx 3500^{14}$C years, and $AV_4 \approx 5500^{14}$C years); Ksudach (Ksh_3 1907; $KS_1 \approx 1800^{14}$C years, and $KS_2 \approx 6000^{14}$C years); Opala ($OP \approx 1500^{14}$C years) [27]; Karymsky ($PZ_3 \approx 3700^{14}$C years) [4]; and Khangar ($KH \approx 7000^{14}$C years), as well as the ash from the Kurilskoe Lake caldera ($KO \approx 7700^{14}$C years) [27], and also the light yellow ash from the base of the deposits of an unknown source, known as the "lower yellow ash" and having an age of $\sim 9000^{14}$C years (V. V. Ponomareva, personal communication). In addition to these, a good local marker is the tephra material of Zavaritsky Volcano (Mt. Peschanaya) ($ZVR \approx 2800^{14}$C years). All of these ashes, except the latter, are yellow, light gray, and light yellow sands, whose particle sizes vary from fine to coarse, their thicknesses ranging between a few millimeters and 5–8 cm, occasionally being as large as 15 cm. The Zavaritsky tephra unit consists of black, stratified, fine- and medium-grained basalt sand with single inclusions of black scoria gravels less than 0.2 cm in size. The unit ranges between 2 and 20 cm in thickness.

Correlation of the particular sections of the deposits lying on the pyroclastic flow and on the hills of the lower sequence with the composite section of the soil–pyroclastic cover (Fig. 6) revealed that these deposits were overlain in all of the sections by the tephra of the Lake Kurilskoe eruption and that the " lower yellow" ash was absent. This places the event under study into the time interval of $7700–9000^{14}$C years B.P. Considering the position of these deposits relative to the tephra markers and assuming the rate of sedimentation to be invariable during this time interval, it can be concluded that the event discussed took place $8000–8500^{14}$C years ago.

Thus, we succeeded in getting an idea about the phenomenology of the event concerned – a combination of a landslide and an explosive eruption, which resulted in the deposition of the lower coarse-clastic sequence and included the development of pyroclastic flows, the deposition of the upper coarse-clastic sequence associated with them, and tephra ejection. We also evaluated an approximate age of the event. However, to verify this model, it is necessary to check whether (or not) this reconstruction of the event is consistent with the eruptive history of the volcano and to what extent it was predetermined by its preceding activity.

In principle, this can be done by analyzing the short and simple history of the volcano. According to many researchers and our view, the volcano was born during the Pleistocene glacial, and by the beginning of the Holocene its edifice grew to the form similar to the modern one. Yet, as late as 9–10 thousand years ago, it continued its moderate extrusive activity accompanied by weak and medium-size explosions. The supporting evidence are its numerous thin tephra layers that were found by O. A. Braitseva and M. M. Pevzner,


T 95-52 m
OP
KS1
AV?
AV?
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KS2
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KO
50-60 m
10-20 m
Composite section
KSHt3
AV1926
OP
KS1
ZVR
AV?
PZ3
AV4
KS2
KH
KO
Lower yellow
1
a
b
2
3
4
5
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KO
7

as well as by us during this study, at the base of the Holocene soil–pyroclastic cover in its surroundings. By the same time, most of the single-act forms were produced: a tuya, extrusive viscous lava domes, and lava cones. One of the latest edifices was a small lava dome that grew on the NE slope of the volcano (9–10 thousand years ago).

It is of interest to compare the chemical compositions of the pyroclastic flow material and of the material of this lava dome. The analyses listed in Table 1 show that the matrix and fragments of the pyroclastic flow bear a very close resemblance to the material of the lava dome. The fact that the soil–pyroclastic cover on the dome surface is older than that on the surface of the pyroclastic flow suggests that the source material of the pyroclastic flow was magma that had intruded the volcano's body, was squeezed out as a dome on the flank, and formed a cryptodome below the summit of the volcano.

It is reasonable to admit, therefore, that by the beginning of the Holocene Bakening was in the closing phase of its evolution [16], [17]. Because of a substantial amount of andesitic extrusive domes and subvolcanic bodies of a similar composition, a normal renewal of volcanic activity must have been accompanied by a significant destruction of the cone, which was what happened during the event discussed. In our opinion this was one of the conditions necessary for the realization of the reconstructed behavior of the eruption discussed.

The other prerequisite condition was tectonic activity. The time when this eruption occurred was a period of the intense reactivation of endogenic processes: tectonic movements, seismicity, and volcanic tectonics [10]. These processes were especially active within young tectonic structures and areas of recent volcanism, which include the Sr. Avacha graben with the Bakening and Novo-Bakening volcanoes and many single-act volcanic formations on its sides [21], [23]. Tectonic reactivations of such areas usually involve significant ground surface deformation, large earthquakes, and voluminous collapses and landslides that accompany them. Apparently, this is what took place in the Bakening area, which is indicated by numerous seismotectonic rockslide avalanches and topographically expressed tectonic faults.

Proceeding from the above considerations, what happened at Bakening can be interpreted as follows. Prior to the eruption discussed, the volcano was an almost regular stratovolcanic cone with several extrusive domes and a tuya on its slopes and at the foot.

Figure 6 Soil-pyroclastic sections from the Bakening area showing major ash markers: *1*, *2* – volcanic ash: *1* – fine- and coarse-grained sand undifferentiated in composition, *2* – gravel and lapilli (*a* – vesicular basalt scoria, *b* – massive andesite and dacite fragments); *3*, *4* – pyroclastic flow and debris avalanche deposits, respectively; *5* – moraine of late Pleistocene glacial; *6* – humic sandy loam; *7* – transit ash index (see the text for explanation).

Its height was ~ 150 m greater than the modern (see Fig. 3). As a result of a viscous lava extrusive activity that dominated at Bakening the latest Pleistocene and the earliest Holocene, several andesitic domes of varying sizes were squeezed out in its near-summit portion and at the slopes, and cryptodome-type subintrusive bodies were intruded into the cone itself. As the result, the upper part of the cone happened to be structurally heterogeneous and more heavy, compared to ordinary stratovolcanoes, because of the intrusion of the dense rocks of the cryptodomes.

Naturally, this unequilibrated state of the cone could not exist long in an unstable tectonic environment, high seismicity, and intense Kamchatkan volcanic activity. The destruction of the cone that took place 8000–8500^{14}C years ago might have been triggered by the reactivation of a peripheral magma chamber under the volcano or by a large earthquake, or both, as a result of which some amount of plastic, half-congealed magma was squeezed out into the cone as a cryptodome and caused a rock failure above it. An example of this phenomenon was a purely seismic collapse and debris avalanche at Ontake Volcano (Japan), where an earthquake of $M = 6.8$ destroyed part of the southern slope ~ 0.037 km^3 in volume. Note, that the form of the resulting cirque bears a close resemblance to that of the crater at Bakening [29].

The following sequence of events seems to be realistic. The process began with the collapse of a large fragment of the near-summit portion of the cone in its SE sector. The resulting cirque exposed the rocks that had been at a depth of a few hundred meters and unroofed the still hot cryptodomes. A rapid decompression led to their fragmentation in a manner similar to a process simulated in laboratory conditions [24], [25]. Under natural conditions the fragmentation of the not fully degassed cryptodomes might have been accompanied by explosions.

The products of the collapse and debris avalanche are the rocks of the lower coarse-clastic sequence. The products of the cryptodome fragmentation are the deposits of the block-and-ash pyroclastic flow (upper coarse-clastic sequence) and tephra.

Because fresh magma did not rise, and the volume of the reactivated cryptodome magma was not sufficient, the eruption did not pass to a plinian phase but was confined to the development of a small pyroclastic flow and the ejection of a moderate volume of tephra. The fallen material of the cone produced a debris avalanche [32], [34], [35], [36] which rolled down into the Sr. Avacha Valley. The pyroclastic flow bifurcated into several tongues, one of which traveled a distance of 3.5 km to the northeast from the volcano as far as the western shore of Lake Bezymyannoe; one tongue moved for some distance along the Sr. Avacha Valley. The longitudinal profile of the Sr. Avacha River channel (Fig. 7) suggests that the debris avalanche traveled down this river valley for a distance of 11–12 km to an elevation of ~ 500 m above sea level. One can see that the total thickness of the deposits in the valley is as large as 150 m (in a compact state). The thickness of the avalanche during its movement was much larger because of entrapped water. Tephra had a much wider dispersal range: ~ 7 km northward, to the northern

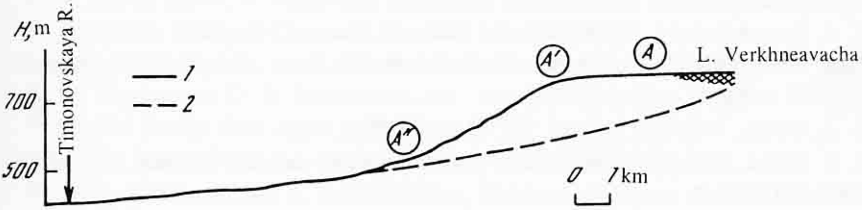

Figure 7 Longitudinal section (*1*) of the Sr. Avacha channel from Lake Verkhneavacha to the Timonovskaya River; *2* – inferred profile of the Sr. Avacha channel prior to the Bakening eruption 8000–8500^{14}C years ago.

shore of Lake Bezymyannoe and 12 km southward to the mouth of the river flowing from the Kolodbishe Creek valley. The eruption destroyed a significant portion of the cone, including part of the crater, and produced a large cirque, open to the southeast, which later grew considerably larger because of the intense erosion of its walls and floor. In the upper reaches of the Sr. Avacha River, the debris avalanche dammed the river to form two lakes, Pra-Bezymyannoe, ~ 3 km^2 in area, and Pra-Avacha, ~ 4 km^2. Later some water was drained from them, and two smaller lakes remained, Bezymyannoe and Verkhneavacha. In the former case, the height of the dam crest was 940–950 m above sea level (as indicated by the elevations of the oldest lake terrace), in the latter, the height was 850–860 m. The debris avalanche caused the formation of a large lahar which traveled much farther along the valley. It is likely that the dams were periodically breached, and mud streams flowed in the Sr. Avacha Valley.

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