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Activity of the Northern Volcano Group According to Drilling Data in the Ushkovsky Crater Glacier, Kamchatka

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Abstract—Long-term investigations in the Ushkovsky Volcano caldera were completed in June 1998 using deep drilling of the crater glacier filling the Gorshkov summit cone. A 212-m ice core containing 354 bands of volcanic ash was obtained. The possibility of using an analysis of these data in paleovolcanic reconstructions of the northern volcano group is discussed.

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INTRODUCTION

Volcanic eruptions are not isolated from the environment. Many of them are life threatening and notably affect human activity. To forecast volcanic catastrophes, detailed long-term data on volcanic activity is needed. Historical records usually include a short time interval, and the information is often insufficient. Thus, the problem of objective chronology of volcanic activity is of high importance. Polar ice caps and Alpine boreal glaciers are the most complete sources of data, which is accumulated and kept in the ice for long periods.

The crater glacier at the Ushkovsky volcano summit (Kamchatka, 56°04' N, 160°28' E) is a unique place to obtain ice-cores for regional paleoclimatic and paleovolcanic reconstructions in the Pacific sector of the Northern Hemisphere. The volcanic summit rises to the middle troposphere (~4000 m above sea level) and, being located at the boundary between the main atmospheric baric centers in the region of Kamchatka (between the Asiatic Maximum and the Aleutian minimum), it contains detailed records of secular fluctuations of regional baric centers, which produce climate changes in Kamchatka, in its glacier. Moreover, ash beds stored in the glacier in chronological order reflect information about activity of surrounding volcanoes.

METHOD OF STUDIES

The joint Russian–Japanese expedition in 1996–1998 carried out a complex of glaciological and geophysical research in the Ushkovsky volcano caldera (Fig. 1), which was performed by drilling a borehole in the glacier filling the Gorshkov crater [12, 13, 19, et

al.]. The 27-m-deep borehole [4, 18] was drilled near the geometric center of the crater in 1996, while pits were used to measure ice mass balance and made it possible to reliably estimate the accumulation rate, which has been approximately 0.6 m/yr in an ice equivalent, for at least the last 28 years.

These data together with the radiolocation data allowed us to construct a mathematical model of the crater glacier dynamics, according to which we determined the optimal location for deep drilling at a distance 200 m from the crater geometrical center, downstream of the ice flow line [16]. The maximal glacier thickness, measured using the radiolocation method, reaches 250 m at this location [11], and the age of the ice at this depth is about 800 years according to the model [19].

The drilling was performed using a GeoTecs Co. electromechanical driller with a designed drilling depth of 200 m (developed by T. Takahashi, Japan). The 212-m-long ice core was extracted almost without loss and was delivered by a refrigerator ship to the core storage at the Low Temperatures Institute, Hokkaido University, for further analysis. The initial core study at the drilling site included stratigraphy description, firn and ice density measurements, and ice electric conductivity measurements (ECMs). Moreover, the whole core was shot using a digital videocamera for further visual analysis using image processing software [19, 21].

Ice cores are studied using different methods. Volcanologic studies are focused on three main problems: specification of the chronology of volcanic eruptions, the study of the peculiarities of individual events, and the estimation of the influence of volcanic ash on the environment based on an analysis of ice geochemical

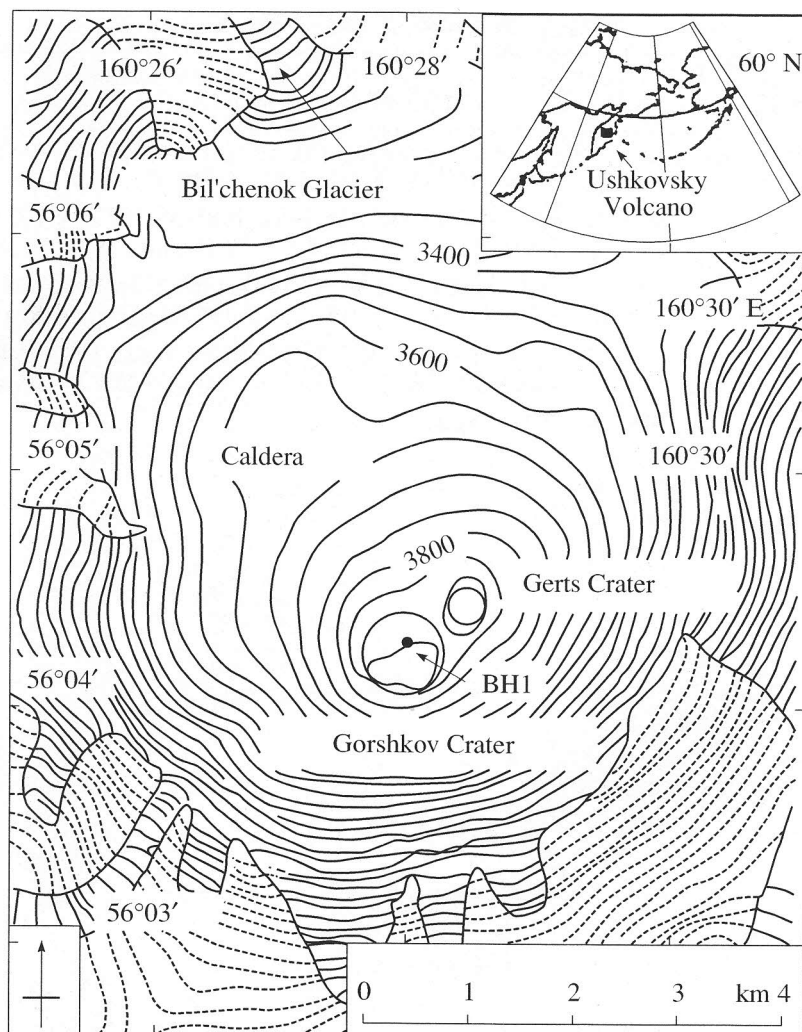


Fig. 1. Topographic scheme of the summit glacial cupola in the Gorshkov crater of the Ushkovsky volcano, Kamchatka, and location of borehole BH-1 drilled in 1998. Solid and dashed lines are the contour lines of the glacier heights and the bedrocks in caldera, respectively. The location of the Ushkovsky volcano in the northern Pacific is shown in the inset.

characteristics. As a first approximation, the first two problems were solved by analyzing the core stratigraphy using the known tephrochronological markers in ice and annual accumulation rate measurements from pits and shallow boreholes in the period from 1984–1999.

DISCUSSION

354 horizons of ash of various chemistry and concentration in the ice were identified in the 212-m-long core. Each horizon corresponds to an individual ash-fall. Since the precise definition of a volcanic eruption is still controversial in volcanology, the basic criterion of eruption division is the lack of ash horizons within a half-period (0.3 m of ice) of annual ice accumulation in the crater. On this basis, we distinguished 180 elementary ash beds and units reflecting individual volcanic eruptions over the last six centuries.

These volcanogenic horizons may include traces from the explosive eruptions of other northern Pacific volcanoes (Table 1). A large distance between the ash emission center and the ash accumulation site testifies to the eruption power and stratospheric effect of ash particle distribution. Therefore, distant volcanoes eruptions with explosivity indices (VEI) of not less than 4 were taken into account in Table 1 [20]. However, in contrast to polar ice cores which mainly contain the transit tephra (or acid signals) of volcanic eruptions located at distances of many hundreds and thousands of kilometers, local eruption ash is mainly encountered in the Ushkovsky core. Hence, we can assume that it is almost impossible to diagnose the level of acid signals, which are registered, e.g., in Greenland cores, within the northern group because of the powerful impact of the ash and gas from local volcanoes [5] on the minor chemical admixtures of distant eruptions accumulated in ice.

Table 1. Explosive volcanic eruptions in the northern Pacific in 1500–2001 [20]

Volcano (region)	Volcano height, m	Geographic coordinates	Explosion dates.
			Volcanic explosivity index (VEI) is specified in parentheses
Shiveluch (Kamchatka)	3395	56.8° N 161.6° E	05/2001(4); 04/1993(3); 1991–1984(1–2); 11/1964(4); 1944(2); 1897(2); 1883(3); 1854(5); 1793(?); 1690(?)C
Klyuchevskoi (Kamchatka)	4850	56.2° N 160.8° E	09/1994(4); 1986(3); 1984–1985(3); 1977(3); 1974(3); 1968(3); 1965(3); 1960(3); 01/1945(4); 1937(3); 1935(3); 1931(4); 1829(4); 1737(4); 1697(3)
Bezmyannyi (Kamchatka)	3000	56.1° N 160.7° E	05/1997(3); 12/1997(3); 1993–1989(2–3); 1986–1984(2–3); 1981–1976(2–3); 02/1979(4)?; 1971(3); 1965–1957(1–3); 1956(5); 1955(4)
Pl. Tolbachik (Kamchatka)	3085	55.9° N 160.5° E	1975–1976(4); 1970(2); 1967(2); 1964(2); 1939–1941(3); 1924(2); 1904(2); 1848(2); 1793(2); 1790–1798(2); 1769(2); 1739–1740(2); 1699(2); 1550(2)T
Karymskii (Kamchatka)	1436	54.0° N 159.5° E	01/1996(2); 05/1963(3)
Avachinskii (Kamchatka)	2743	52.3° N 159.1° E	02/1945(4); 1926(3); 1827(3)
Ksudach (Kamchatka)	1079	51.8° N 157.5° E	03/1907(5)
Alaid (Kurils)	2339	50.8° N 155.5° E	04/1981(4); 1793(4+)
Chikurachki (Kurils)	1817	50.3° N 155.5° E	11/1986(4); 12/1853(4); 1690(4)T
Sinarka (Kurils)	934	48.9° N 154.2° E	?1873(4)
Raikoke (Kurils)	551	48.3° N 153.2° E	02/1924(4); 1778(4)
Sarychev Peak (Kurils)	1497	48.1° N 153.2° E	11/1946(4)
Chirpoi (Kurils)	624	46.5° N 150.9° E	12/1712(4?)
Gareloi (Aleutians)	1573	51.8° N 178.8° W	08/1980(4)
Isanotski (Aleutians)	2446	54.8° N 163.7° W	03/1825(4)
Katmai (Alaska)	841	58.3° N 155.2° W	06/1912(6)
Augustine (Alaska)	1227	59.4° N 153.4° W	10/1883(4)
Pogromni (Aleutians)	2002	54.6° N 164.7° W	? 1795(4)
Tarumai (Japan)	1024	42.7° N 141.4° W	08/1739(5); 08/1667(5)
Usu (Japan)	725	42.5° N 140.8° W	08/1663(5)

Note: (C) radiocarbon dating; (T) tephrochronological dating; the remaining dates (?) are historical records (with differences in literature recordings).

The Klyuchevskoi, Shiveluch, Bezmyannyi, Ploskii Tolbachik and Ushkovsky volcanoes are the closest formations to the drilling site among the active volcanoes in the region (Fig. 2). The eruption products of these volcanoes are to a certain degree present in this core. The deposition ages of the majority of the

ash horizons within the upper 40 m, which have accumulated for the last 50 years, are known.

A granulometric analysis made for 43 ash samples revealed their generally psammitic grain size, and only 6 samples contained psephitic grains (>2.0 mm). These are mainly from ash represented by the most

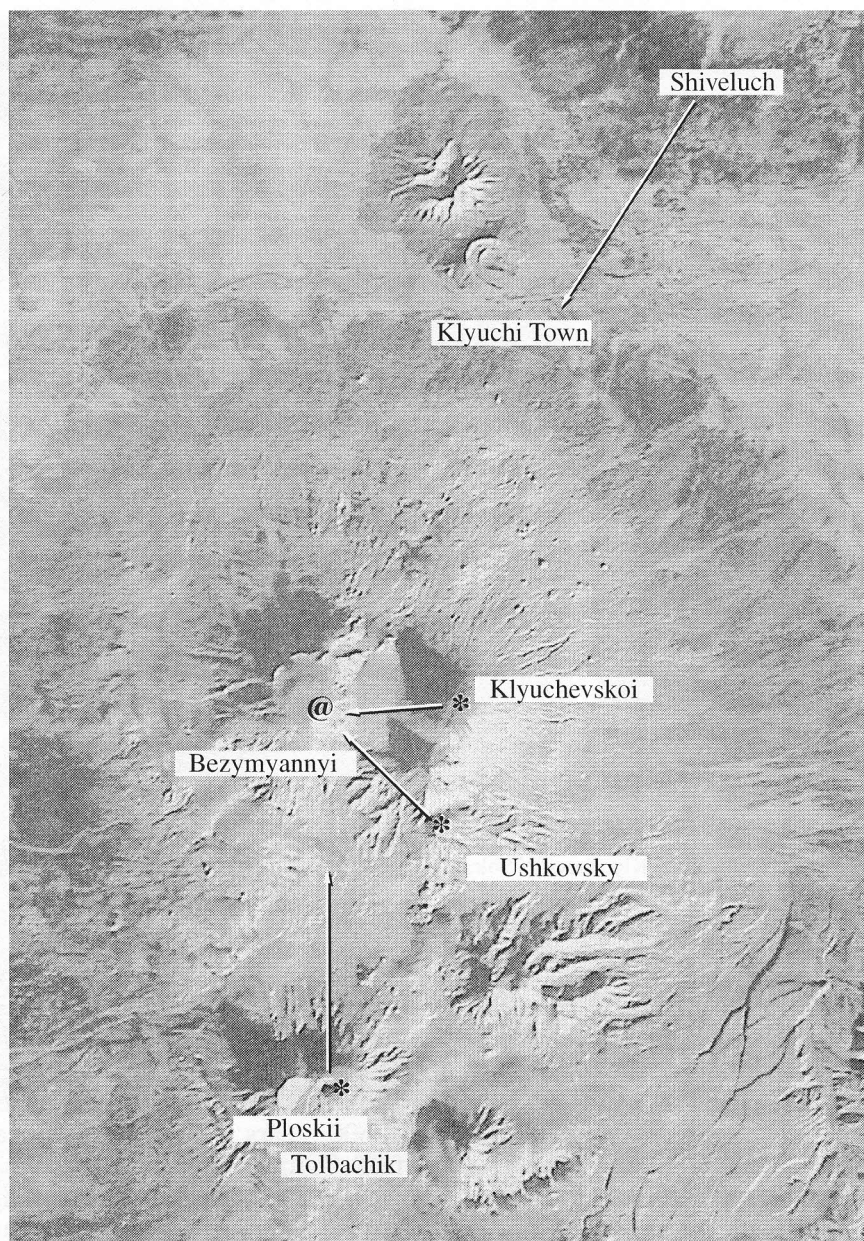


Fig. 2. The location of active volcanoes of the northern group relative to the drilling site (@). Stars mark the volcano craters, arrows are directed toward the Ushkovsky volcano summit.

concentrated horizons of thickness 0.5–2.0 cm in the core (Fig. 3).

The relationships between rock fragments, obsidian, and crystalline phases are shown in Fig. 4. These relationships indicate that the core ash is mostly represented by lithoclastic and vitroclastic varieties. Crystalloclastic ash is encountered very rarely. As an example, the crystalline phase in the ash from a depth of 108.7 m, corresponding to a deposition date in the second half of the 18th century, [14] consisted of plagioclase crystal fragments.

Mineralogy and chemistry of the ash indicated that this ash is mostly basaltic and only sometimes andes-

itic. A comparison of the ash composition in the core with vulcanites from recent eruptions of the northern group of volcanoes made it possible to perform paleovolcanological reconstructions. These reconstructions determined that specific ash beds originated in particular eruptive centers.

BRIEF CHARACTERIZATION OF ACTIVE VOLCANOES OF THE KLYUCHEVSKOI GROUP

The Klyuchevskoi volcano is the highest (4850 m in 1994) and the most active volcano of this group. It is located at a distance of 10 km from the Ushkovsky

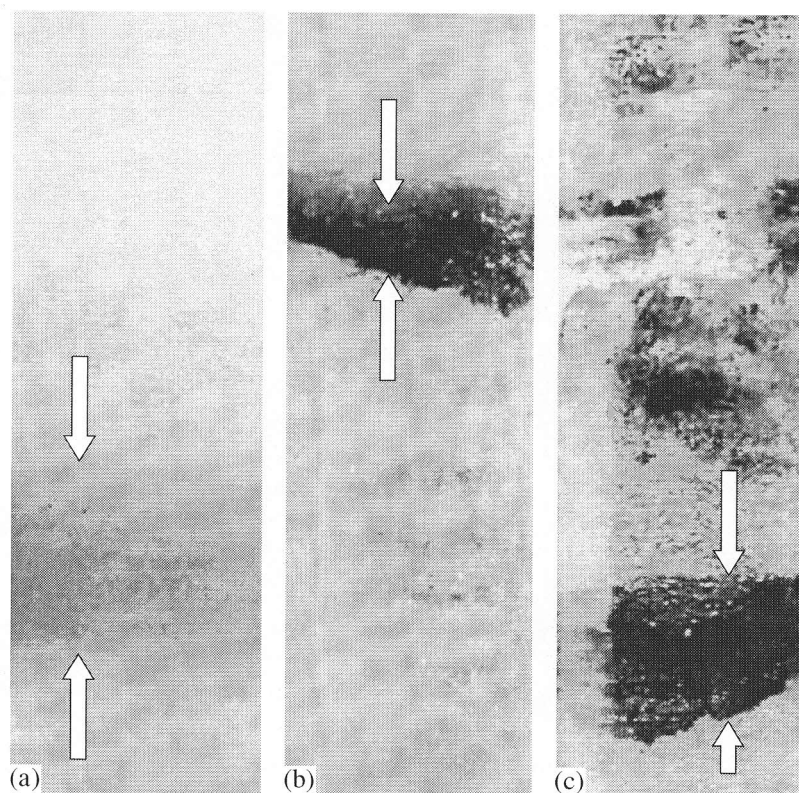


Fig. 3. Examples of ash interlayers in the core: (a) “muddy” ice at a depth of 73.36 m saturated with the finest ash grains of far eruptions (3 cm thick); (b) distinct ash interlayer of the Klyuchevskoi volcano eruption in 1852–1854 at a depth of 86.44 m; (c) 2 cm thick ash interlayer of the Klyuchevskoi volcano eruption in 1829.

volcano summit and is higher than this volcano by 1 km. Therefore, the core tephra is mostly from the Klyuchevskoi volcano. Dark gray or almost black basaltic ash from the Klyuchevskoi volcano characterizes the glacial structure. The heaviest ashfalls (six events), during which the thickness of the sediments reached 1–2 cm (Fig. 3), occurred in the 18–19th century, and the location of these sediments in the ice core correlates well with the results of model calculations (Fig. 5) for the paroxysmal eruptions that occurred in 1737 and 1829.

Shiveluch (80 km from Ushkovsky) is an andesite stratovolcano which has experienced disastrous explosive eruptions. Light grey tephra from this volcano, including black crystals of amphibole, is usually tinted light yellow, pale, or brown when found far from the volcano. Several ash horizons in the core were deposited during the times when eruptions of this volcano occurred, e.g., 260–300 years ago (Sh-1 in [10]) and as well in 1854 (although the eruptive cloud in 1854 moved mainly to the north of the volcano). To resolve these horizons, it is necessary to perform chemical and mineralogical analyses on the entire ash collection.

The other andesite volcano in the group is Bezymiannyi (14 km from the drilling site). This volcano

became widely known after its eruption on March 30, 1956. The ash layer formed as a result of this eruption is the thickest from the 20th century (nearly 1.5 cm) in the studied core. However, this is the only layer of the Gorshkov ice core originating at Bezymiannyi for the last 600 years because the volcano was dormant before October 1955. After activation for the last 50 years, ash from this volcano in the core is the second most common representative (after the Klyuchevskoi ash) and is colored light gray and sometimes yellowish brown.

Ploskii Tolbachik (30 km south of the Ushkovsky volcano) is an active basaltic Kamchatka volcano. Although weak explosive eruptions are predominant, several paroxysmal events should have been recorded in the Ushkovsky glacier stratigraphy. The geographical location of this volcano in the southern part of the Klyuchevskoi group does not favor northward distribution of its ash cloud because northwestern, western, and northeastern winds dominate in this region.

The Ushkovsky volcanic ash may also be present in the glacier section. Solfatara activity and increased geothermal flow in the summit craters of the volcano evidences its possible eruptions in a recent past. According to Gerts [7], a weak explosive eruption probably occurred in the spring of 1890. Determina-

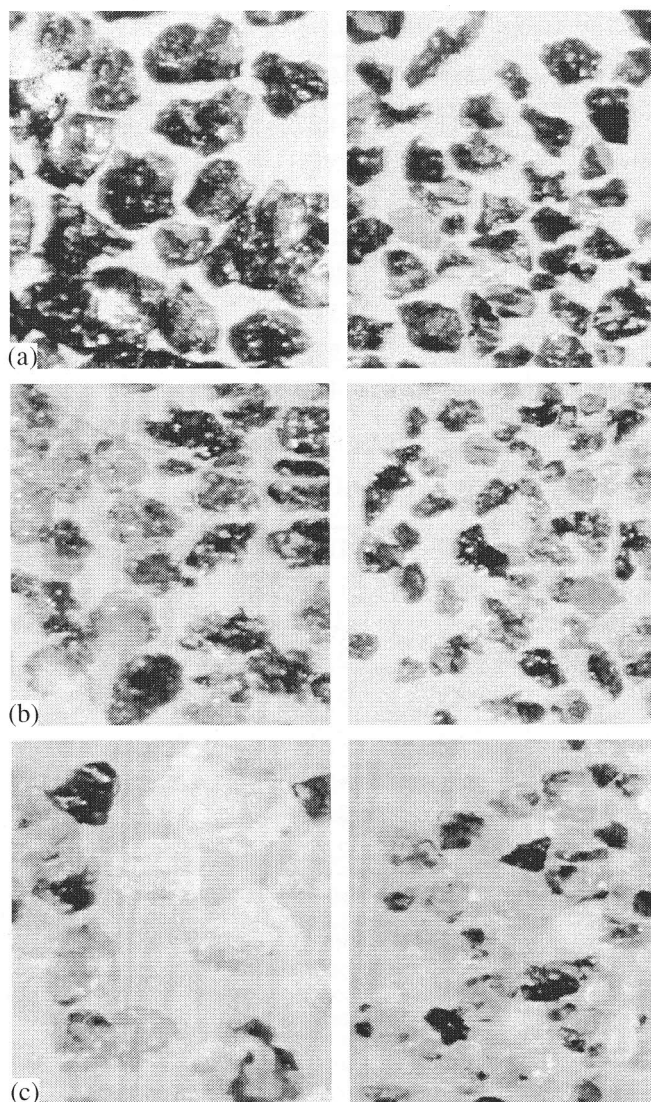


Fig. 4. The relationship of obsidian, rock fragments, and crystalline phase in ashes from the core: (a) lithoclastic, (b) vitroclastic, and (c) crystalloclastic particles. The fractions are shown in the columns: 1–0.5 (left) and 0.5–0.25 (right), respectively.

tion of the presence of Ushkovsky eruption ash in the ice core will be made after the completion of our analytic work.

Ten layers of muddy ice (Fig. 3a), containing the finest lithic grains as a condensation nuclei of snow flakes and thin ash of pelitic size were also found in the core. Some of these layers can be considered as the transit ash from distant eruptions, dust storms in northern China and Mongolia, or forest fires.

The volcanoes are located close to each other, and their pyroclastics substantially differ in composition and thus are rather confidently identified by mineralogy and chemistry. To identify the volcanic center related to any band in our core, we considered the pet-

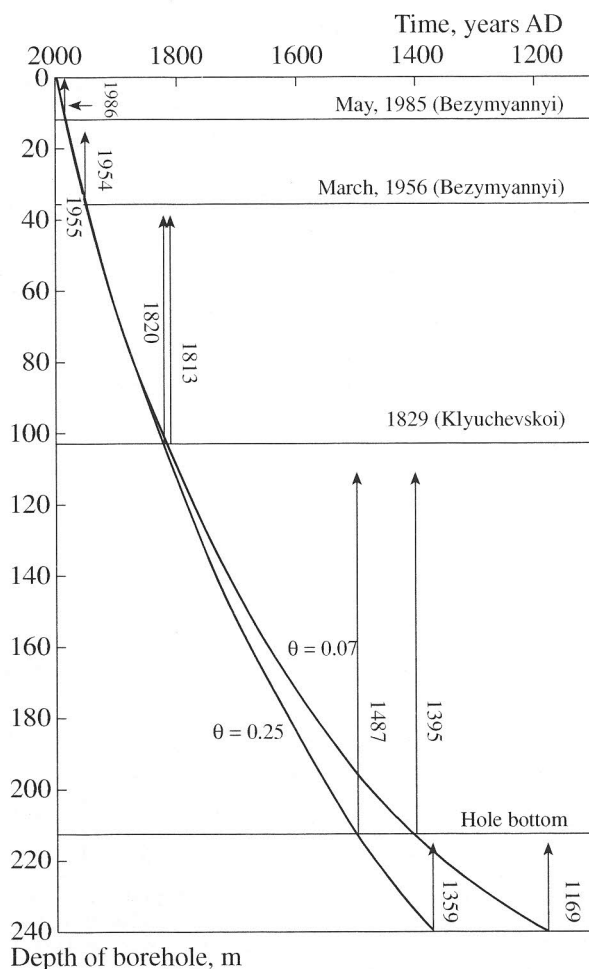


Fig. 5. Calculated age of the ice beds in the crater glacier according to their depths. Two models of bottom melting are considered taking allowance for the heat flow power. Vertical arrows with numbers show the difference between ash markers and the dating made by A.N. Salamatina [10, 13].

rochemical peculiarities of the erupted products from these volcanoes.

Aluminous and magnesia basalts have recently erupted from the Klyuchevskoi and Ploskii Tolbachik volcanoes. To characterize the Ploskii Tolbachik basalts, we took mean chemical analyses of the ash from the central crater and the northern and southern outbreaks of the Great Fissure Tolbachik Eruption (GFTE) in 1975–1976. For the Klyuchevskoi volcano, all types of basalt from the Holocene and recent eruptions were used. Tables 2 and 4 demonstrate that aluminous basalts of the Ploskii Tolbachik volcano differ from those of the Klyuchevskoi volcano in their composition of rock-forming oxides and in petrochemical parameters. Magnesian basalts of these volcanoes also differ in their main petrochemical parameters and the composition of some rock-forming oxides. Thus, ash from these volcanoes is quite different in its chemistry and petrochemical characteristics.

Table 2. Chemistry of erupted rocks of the Klyuchevskoi and Ploskii Tolbachik volcanoes, mass %

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O
1 t	51.16	1.94	15.70	3.50	7.96	0.19	4.57	7.96	3.63
2 t	51.19	1.72	16.21	4.09	6.84	0.16	5.21	8.06	3.44
3 t	49.90	1.05	14.56	5.19	4.59	0.16	8.04	12.48	2.70
4 t	49.92	0.97	12.50	3.65	6.06	0.16	11.39	12.41	2.18
1 k	52.31	0.77	14.75	8.09*		0.20	10.14	9.28	2.45
2 k	53.08	0.86	16.45	8.56*		0.19	7.04	8.99	2.92
3 k	51.98	0.91	18.27	5.87	3.71	0.22	5.86	8.01	3.04
4 k	53.31	0.95	18.58	3.09	5.54	0.15	4.79	8.19	3.31
5 k	54.64	1.28	17.62	4.34	5.12	0.15	4.14	6.12	3.62
Sample	K ₂ O	H ₂ O ⁻	H ₂ O ⁺	P ₂ O ₅	Σ	Na ₂ O + K ₂ O	Na ₂ O/K ₂ O	al'	f'
1 t	2.34	0.36	0.35	0.53	100.19	5.97	1.55	0.98	18.16
2 t	2.22	0.09	0.23	0.56	100.02	5.66	1.55	1.01	18.03
3 t	1.20	0.14	0.26	0.19	100.46	3.90	2.25	0.82	19.03
4 t	0.96	0.12	H.O.	0.2	100.49	3.11	2.34	0.59	22.23
1 k	0.70	—	—	0.20	98.89	3.15	3.50	0.81	19.2
2 k	1.06	—	—	0.20	99.35	3.98	2.76	1.06	16.65
3 k	1.13	H.O.	0.39	0.19	99.59	4.17	2.69	1.18	16.57
4 k	1.25	0.26	H.O.	0.5	99.57	4.56	2.65	1.38	14.52
5 k	1.40	0.18	0.53	0.23	99.95	5.02	2.59	1.30	15.03

Note: (1 t) Ash from the Ploskii Tolbachik central crater eruption (mean of 9 determinations) analyzed by G.P. Novoseletskaia; (2 t) ash from the southern outbreak of the Great Fissure Tolbachik Eruption (GFTE) in 1975–1976 analyzed by N.R. Gusakova; (3 t) ash from the northern outbreak of GFTE erupted on August 2, 1975; (4 t) ash from the northern outbreak of GFTE erupted on July 26, 1975; (3 t), (4 t) analyzed by T.G. Osetrova; (1 k) the rock of Holocene cinder cone of the Klyuchevskoi volcano [3]; (2 k) the rock of Bilyukai cinder cone (mean of 18 determinations) [3]; (3 k), (4 k), and (5 k) ash of the Klyuchevskoi volcano eruptions in: (3 k) July 13–14, 1984, analyzed by A.M. Okruglina; (4 k) June 26, 1984; (5 k) February 19, 1987, analyzed by G.P. Novoseletskaia.

The erupted products of the Ushkovsky and Shiveluch volcanoes have an andesite composition, while the composition of recent rocks of the Bezmyannyi volcano varies from andesite to basaltic andesite (Table 3). Ash of these volcanoes differs in its SiO₂, Fe₂O₃, FeO, and K₂O content. This ash also differs in its alkali ratio and other petrochemical parameters (Table 4). Two kinds of eruptions, which should be taken into account in an analysis of the event chronology, are typical of the Shiveluch and Bezmyannyi volcanoes.

The first type of eruption combines disastrous explosive eruptions of a directed blast type with destruction of the construction and the carrying out of a huge amount of juvenile material. Such eruptions of the Shiveluch volcano take place every 100–300 years. An eruption of the Bezmyannyi volcano occurred on March 30, 1956, after a dormant period that lasted 900–1000 years. Andesite ash in the ice core dated earlier than 1956 belongs to the Shiveluch or other Kamchatka volcanoes.

The second-type eruptions are extrusive–explosive eruptions. Such eruptions of the Bezmyannyi volcano began to occur immediately after the disastrous 1956 eruption and still continue with some interruptions. After the disastrous Shiveluch eruption in 1964, the second-type eruptions began in 1980 (i.e., 16 years later) and are still occurring.

Complete recording of volcanic events becomes problematic when the stratigraphy of the ice cores is interpreted. Due to meteorological factors (wind direction, tropopause height in various seasons, etc.) and the differing duration and power of individual eruptions, some present-day events are not registered in the core. In these cases the general configuration of volcanic activity is determined with certain analyses (chemical, isotopic–geochemical, and ice conductivity measurements).

It should be noted that the dating of significant ash bands in the core done by experts and the known historical records obtained from the Salamatin model are in good agreement [16]. The ash beds from the 1945, 1829, and 1737 eruptions of the Klyuchevskoi vol-

Table 3. Chemistry of erupted rocks of Bezmyannyi, Shiveluch, and Ushkovsky volcanoes, mass %

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	Fe ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O
1 B	59.94	0.88	17.57	3.17	3.22	0.14	2.81	6.97	3.08	1.32
2 B	56.54	0.81	18.10	4.51	3.02	0.10	3.98	7.67	3.22	1.24
3 B	60.62	0.57	17.77	3.45	2.61	0.13	2.51	6.83	3.46	1.58
4 B	60.86	0.71	17.67	2.59	3.28	0.10	3.56	5.70	3.33	1.55
5 B	60.70	0.90	17.40	3.28	2.65	0.08	3.04	5.94	3.55	1.61
1 Sh	59.38	0.63	16.56	4.12	1.97	0.13	4.53	6.50	3.87	1.40
2 Sh	62.48	0.53	16.52	2.49	1.79	0.15	3.83	6.21	3.57	1.15
3 Sh	61.74	0.40	17.87	2.94	1.87	0.12	2.80	5.80	3.52	1.27
4 Sh	63.06	0.61	16.73	2.67	1.96	0.02	1.68	6.40	3.56	1.32
1 U	59.38	0.97	18.50	1.73	4.28	0.09	1.92	6.30	3.52	2.11
2 U	58.06	0.92	17.54	1.59	5.75	0.12	3.90	6.22	3.40	1.68
Sample	H ₂ O ⁻	H ₂ O ⁺	P ₂ O ₅	SO ₃	Σ	Na ₂ O + K ₂ O	Na ₂ O/K ₂ O	al'	f'	
1 B	—	—	—		99.82	5.12	2.88	1.91	10.22	
2 B	0.21	0.25	0.28		99.93	4.46	2.60	1.57	12.42	
3 B	0.47	—	0.21		100.21	5.04	2.19	2.07	9.27	
4 B	0.30	0.15	0.59		100.42	4.88	2.15	1.88	10.24	
5 B	0.04	0.16	0.19		99.54	5.16	2.20	1.91	9.95	
1 Sh	0.48	0.16	0.21		99.97	5.27	2.76	1.56	11.38	
2 Sh	0.24	0.58	0.19		99.55	4.72	3.10	2.04	8.61	
3 Sh	0.13	0.92	0.29		99.54	4.79	2.77	2.35	8.13	
4 Sh	—	1.66	0.13		99.82	4.88	2.70	2.65	6.94	
1 U	0.45	0.48	0.55		100.28	5.63	1.67	2.33	8.99	
2 U	0.45	0.12	0.30		100.05	5.08	2.02	1.56	12.28	

Note: (B) Bezmyannyi; (Sh) Shiveluch; (U) Ushkovsky. (1 B) andesite of the 1956 eruption analyzed by I.I. Tovarova [2]; (2 B) basaltic andesite of Novyi cupola eruption in 1985 (mean of 20 determinations) analyzed by N.R. Gusakova and G.F. Knyazeva [1]; (3 B) ash of the 1984 eruption (sampled at Apakhonchich seismic station) analyzed by N.R. Gusakova [8]; (4 B) ash of the 1985 eruption (mean of 5 determinations), analyzed by N.R. Gusakova and G.F. Knyazeva [1]; (5 B) ash of the 1995 eruption (sampled in Klyuchi town, 40 km from the crater) analyzed by L.A. Kartasheva [6]; (1 Sh) andesite of volcanic eruptions (mean of 46 determinations) [3]; (2 Sh), (3 Sh), and (4 Sh) products of the 1993 volcanic eruption, analyst is not mentioned [9]; (2 Sh) shivers from the pyroclastic flow (mean of 2 determinations) [9]; (3 Sh) ash sampled at a distance of 25 km from the volcano; (4 Sh) ash sampled at a distance of 30 km from the volcano; (1 U) andesite from the Gorshkov cone summit; (2 U) andesite from the Gerts cone summit; samples (1 U)–(2 U) were analyzed by N.R. Gusakova.

Table 4. Variations in the petrochemical parameters of ashes from the northern group volcanoes (Kamchatka)

Volcano	Rock	Petrochemical parameters			
		Na ₂ O + K ₂ O	Na ₂ O/K ₂ O	al'	f'
Ploskii Tolbachik	Magnesite basalt	3.11–3.90	2.25–2.34	0.59–0.82	19.03–22.23
Klyuchevskoi	Magnesite basalt	3.15–3.98	2.76–3.50	0.81–1.06	16.65–19.20
Ploskii Tolbachik	Alumina basalt	5.66–5.97	1.55	0.98–1.01	18.03–18.16
Klyuchevskoi	Alkali-calk basalt	4.17–5.02	2.59–2.69	1.18–1.38	14.52–16.57
Bezmyannyi	Alkali-calk andesite	4.88–5.16	2.15–2.20	1.88–2.07	9.27–10.24
Shiveluch	Alkali-calk andesite	4.79–4.88	2.70–2.77	2.35–2.65	6.94–8.13

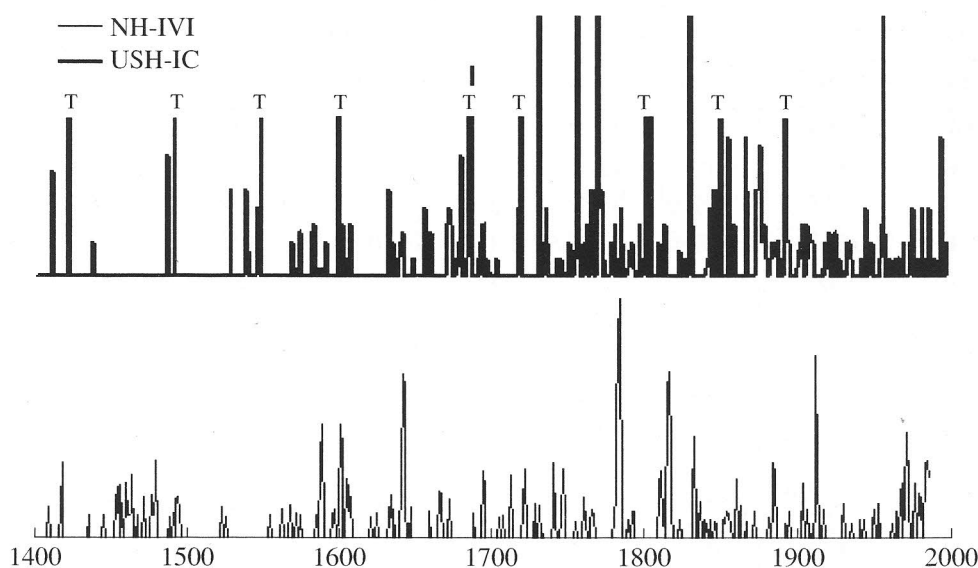


Fig. 6. Ice-core volcano index (IVI) for the Northern Hemisphere [9] an acidity signal, measured in units of standard deviation from the background level, and the index of ashfall power (USH-IC) of the northern group volcano eruptions according to the records in the Ushkovsky core (in mm of ash interlayer thickness). T is transit ash or particles related to dust storms or forest fires.

cano, the tephra of the Bezmyannyi volcano from 1955–1956 and several other eruptions nearly coincide with the calculated curve (Fig. 5). Hence, we draw the first regional paleoclimatic conclusion that the annual accumulation in the Ushkovsky volcano crater has not substantially changed for at least the three previous centuries.

Our determinations of the composition and concentration of volcanic ash and aerosols in the section should improve estimates of the volcanogenic load on the regional atmosphere as well as helping determine the impact of the powerful effusive and effusive–explosive volcanic eruptions of the northern group that did not leave tephra layers in the glacier (for example, the paroxysmal Klyuchevskoi volcano eruptions in October 1, 1994). The analyzed cores from shallow boreholes drilled in 1996 and 1997 clearly demonstrate fluctuation of isotopic and chemical signals, in which the stable isotopes of oxygen and hydrogen and pH show seasonal cycles and different natural trends.

It is also interesting to compare the Ushkovsky chronology of volcanic activity (USH-IC) with Robock ice-core volcano index (IVI) [15], which is the index of global volcanic variables obtained from combination of several series of acidity and sulfate concentrations in ice cores [4]. The upper panel of Fig. 6 shows the long-term trend of ashfall power index for the northern group volcanic eruptions according to the Ushkovsky core interpretation (USH-IC in mm of ash bed thickness). A comparison of these graphs shows the absence of direct correlation between the regional and global (IVI of the Northern Hemisphere) chronol-

ogies. At the same time, secular changes in volcanic activity show correlation, especially for the period from the middle of the 16th century to the beginning of the 20th century. If we consider only the Klyuchevskoi volcano eruptions in our chronology, the correlation with IVI will likely become closer.

CONCLUSIONS

Our studies of the ice core from the Ushkovsky volcano crater significantly improve our understanding of the chronology and power of the Kamchatka volcano eruptions (especially for the active volcanoes of the northern group). Data on glacial accumulation for the last 50 years, marking ash layers, and mathematical modeling of the crater glacier dynamics [17], allows us to estimate the age of the ice layers at the borehole bottom at 600 ± 50 years. It is known that no powerful or moderate eruptions of the Ushkovsky volcano summit craters occurred during the period.

Ash from 180 volcanic eruptions (Fig. 7) is recognized in the core for the past centuries, including 49, 38, and 25–30 eruptions in the 20th, 19th, and 16–18th centuries, respectively. From this it follows that the activity of the northern group volcanoes was higher in the 20th century than in the past 500 years by a factor of 1.5. However, we should note that almost all powerful eruptions (mainly of the Klyuchevskoi volcano) occurred in the 18–19th centuries (ten of 13 events), while not more than one event occurred during each of the other centuries.

This analysis was performed only using observed ash horizons. It is clear that more precise geochemical

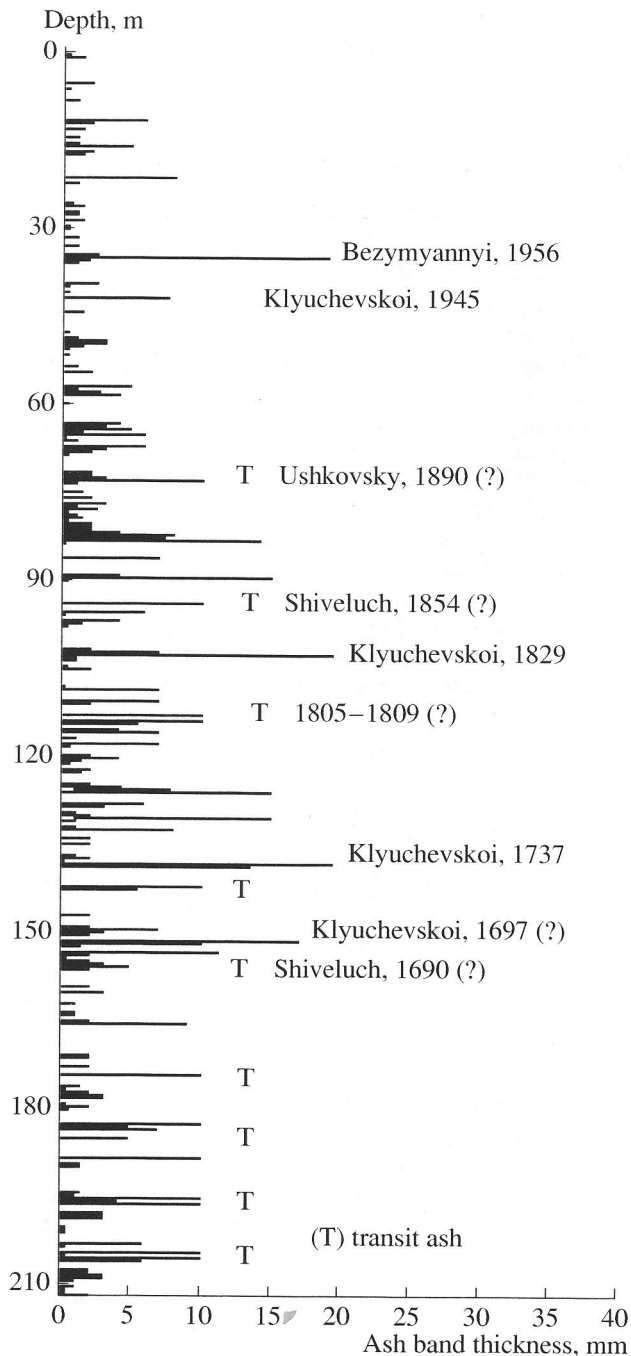


Fig. 7. Distribution of the ash horizons in the Ushkovsky ice core, including the dates of the known northern group volcano eruptions. T is transit fine ash of remote volcanoes, sign (?) means uncertain dating.

and isotopic techniques will substantially increase the information value of the ice core. This is especially important for the Shiveluch volcano, which is the farthest volcano from the drilling site.

On the whole, we note that the Gorshkov crater glacier on the Ushkovsky volcano is not only a paleoclimatic archive for the northern Pacific sector of the

Earth [19] but can also be used to construct the 600-year chronology of volcanic activity in the region. Some Kamchatka volcano eruptions for this period will most likely be dated using acid and sulfate signals in ice cores from the Alaska Peninsula where volcanic activity is not so intense.

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