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The caldera-forming eruption of Ksudach volcano about cal. A.D. 240: the greatest explosive event of our era in Kamchatka, Russia

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Abstract

The largest Plinian eruption of our era and the latest caldera-forming eruption in the Kuril–Kamchatka region occurred about cal. A.D. 240 from the Ksudach volcano. This catastrophic explosive eruption was similar in type and characteristics to the 1883 Krakatau event. The volume of material ejected was 18–19 km^3 (8 km^3 DRE), including 15 km^3 of tephra fall and 3–4 km^3 of pyroclastic flows. The estimated height of eruptive column is 22–30 km. A collapse caldera resulting from this eruption was 4×6.5 km in size with a cavity volume of 6.5–7 km^3. Tephra fall was deposited to the north of the volcano and reached more than 1000 km. Pyroclastic flows accompanied by ash-cloud pyroclastic surges extended out to 20 km. The eruption was initially phreatomagmatic and then became rhythmic, with each pulse evolving from pumice falls to pyroclastic flows. Erupted products were dominantly rhyodacite throughout the eruption. During the post-caldera stage, when the Shtyubel cone started to form within the caldera, basaltic-andesite and andesite magma began to effuse. The trigger for the eruption may have been an intrusion of mafic magma into the rhyodacite reservoir. The eruption had substantial environmental impact and may have produced a large acidity peak in the Greenland ice sheet.

1. Introduction

During the last 10,000 years, five catastrophic explosive caldera-forming eruptions took place in Kamchatka (Table 1): three occurred at the Ksudach volcanic massif and two were associated with the formation of the Karymsky and Kuril Lake–Iliinsky calderas (Braitseva et al., 1992, 1994). Four of these five eruptions occurred during the first half of the Holocene between 9000 and 6000 yr B.P. During the second half of the Holocene only one caldera-forming eruption (KS_1) took place in Kamchatka, resulting in the collapse of caldera V at Ksudach volcano about 1800 yr B.P. (Figs. 1 and 2). Its characteristics show that this was the second largest Holocene eruption in Kamchatka, after that associated with the formation of Kuril Lake–Iliinsky caldera, and the greatest explosive event in Kamchatka in our era. It was similar in type and characteristics to the 1883 Krakatau eruption and may have produced a large acidity peak in the Greenland ice sheet. Tephra-fall KS_1 covers almost all Kamchatka and is one of the most important marker horizons for the Holocene deposits.

This paper presents the first detailed account of the stratigraphy, age, composition and deposit volume for this eruption. The characteristic features helpful for identification and correlation of KS_1

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Table 1
Holocene caldera-forming eruptions in Kamchatka

Caldera	Eruption code	^{14}C age (yr B.P.)	Genetic types of deposits	Composition of products	Mineral assemblage	Volume of erupted products [a] (km^3)	Caldera size (km)
Ksudach c. V	KS_1	1800	Pyroclastic flow and surge, tephra fall	rhyodacite	Pl + Px + Mt	18–19	4 × 6.5
Ksudach c. IV	KS_2	6000	Pyroclastic flow and surge,	andesite	Pl + Px + Mt	9–11	5 × 6
	KS_3	6100	tephra fall, explosion breccia	dacite rhyodacite	Pl + Px + Mt		
Ksudach c. III	KS_4	8800–8700	Pyroclastic flow and surge, tephra fall, explosion breccia	andesite dacite	Pl + Px + Mt	2	2 × 3?
Karymsky c.	KRM	7800–7700	Pyroclastic flow and surge, tephra fall	dacite rhyodacite	Pl + Px + Mt + Ilm	13–16	5 × 6.5
Kuril Lake–Iliinsky c.	KO	7700–7600	Pyroclastic flow and surge, tephra fall	rhyodacite	Pl + Px + Mt + Hb	120–140	8 × 14

[a] not DRE.

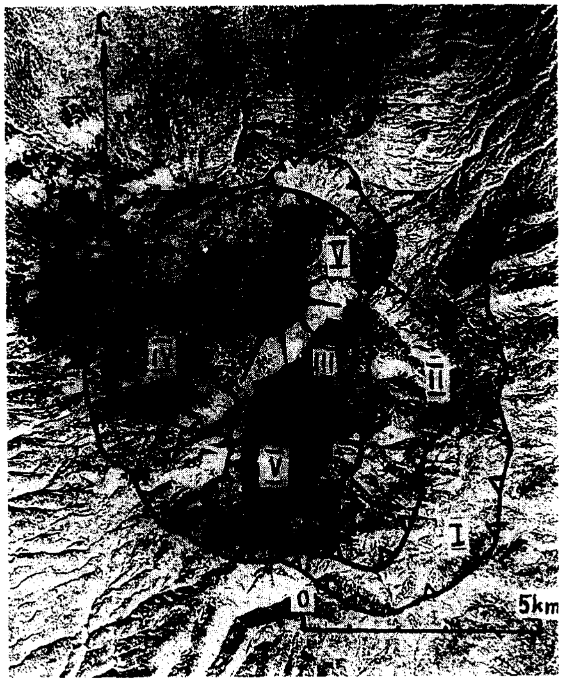


Fig. 1. Calderas of Ksudach volcanic massif. *I* and *II*, Late Pleistocene calderas; *III*, *IV* and *V*, Holocene calderas.

tephra and the area of its dispersion are considered. We reconstruct the course of the eruption and evaluate its environmental impact.

2. KS_1 and the eruptive history of Ksudach volcano

Ksudach volcano consists of a shield-like complex surmounted by nested calderas formed during five collapse events (Fig. 1). Two calderas (I and II) formed in the latest Pleistocene times and three (III, IV and V) during the Holocene (Melekestsev and Sulerzhitsky, 1990; Selyangin, 1990). Codes and ages of explosive eruptions associated with the formation of Holocene calderas are from Braitseva et al. (1992, 1994).

Caldera III was formed roughly 8800–8700 yr B.P. The eruption produced pyroclastic flows and tephra fall (KS_4, Fig. 3). The ash fall spread to the southwest. Eruption products were dominantly andesites, with a total volume of about 2 km^3.

Caldera IV formed as a result of two nearly coeval eruptions KS_3 and KS_2 that occurred approximately 6000 and 6100 yr B.P. Both eruptions produced pyroclastic flows and tephra falls. The ash-fall axis of KS_3 was directed westward and that of KS_2 northward (Braitseva et al., 1992). Pyroclastic deposits of KS_3 range from dacite to rhyodacite, but those of KS_2 are uniformly andesite. The position of caldera IV, which formed after the KS_3 and KS_2 eruptions, is shown in Figs. 1 and 4.

The latest caldera-forming (caldera V) eruption, KS_1, which is the subject of this study, was separated from the previous caldera-forming eruption KS_2 by a 4300-yr interval. During that interval, at least four eruptions occurred from Ksudach. The three smaller eruptions produced only moderate ash-fall deposits, and one large eruption produced about 0.5 km^3 of tephra, called the "bomb tuff" (KSbt in Fig. 3), because it contains large bombs of dacitic pumice. That eruption apparently took place about 4500–4000 yr B.P., since its tephra is bracketed stratigraphically between the tephra marker horizons of Khodutka (KHD 2800 yr B.P.) and Zheltovsky (ZLT about 5000 yr B.P.) volcanoes (Fig. 3).

After the caldera V collapse had taken place, the Shtyubel stratovolcano began to grow within this caldera. All subsequent voluminous eruptions from Ksudach, including the historical one in 1907, originated from the Shtyubel cone.

3. The KS_1 deposits

The caldera-forming eruption deposits comprise pyroclastic flows, pyroclastic surges and tephra falls.

Pyroclastic-flow deposits fill the river valleys on the northern, western, and eastern slopes of the volcano and form an extensive cover to the north of it. They are also present within older caldera depressions of the central part of the massif (Fig. 4). Deposits include poorly consolidated, white, fine- or coarse-grained tuff with fragments of light-colored pumice. Deposits are commonly non-stratified: sometimes lense-shaped clusters of pumice bombs occur. Non-juvenile material generally makes up only a few percent of the deposits. However, some outcrops have fragments of old lavas and altered rocks constituting as much as 10% of the total volume.

Four pyroclastic-flow units separated by pumice bomb fall horizons are identified in the valley of the

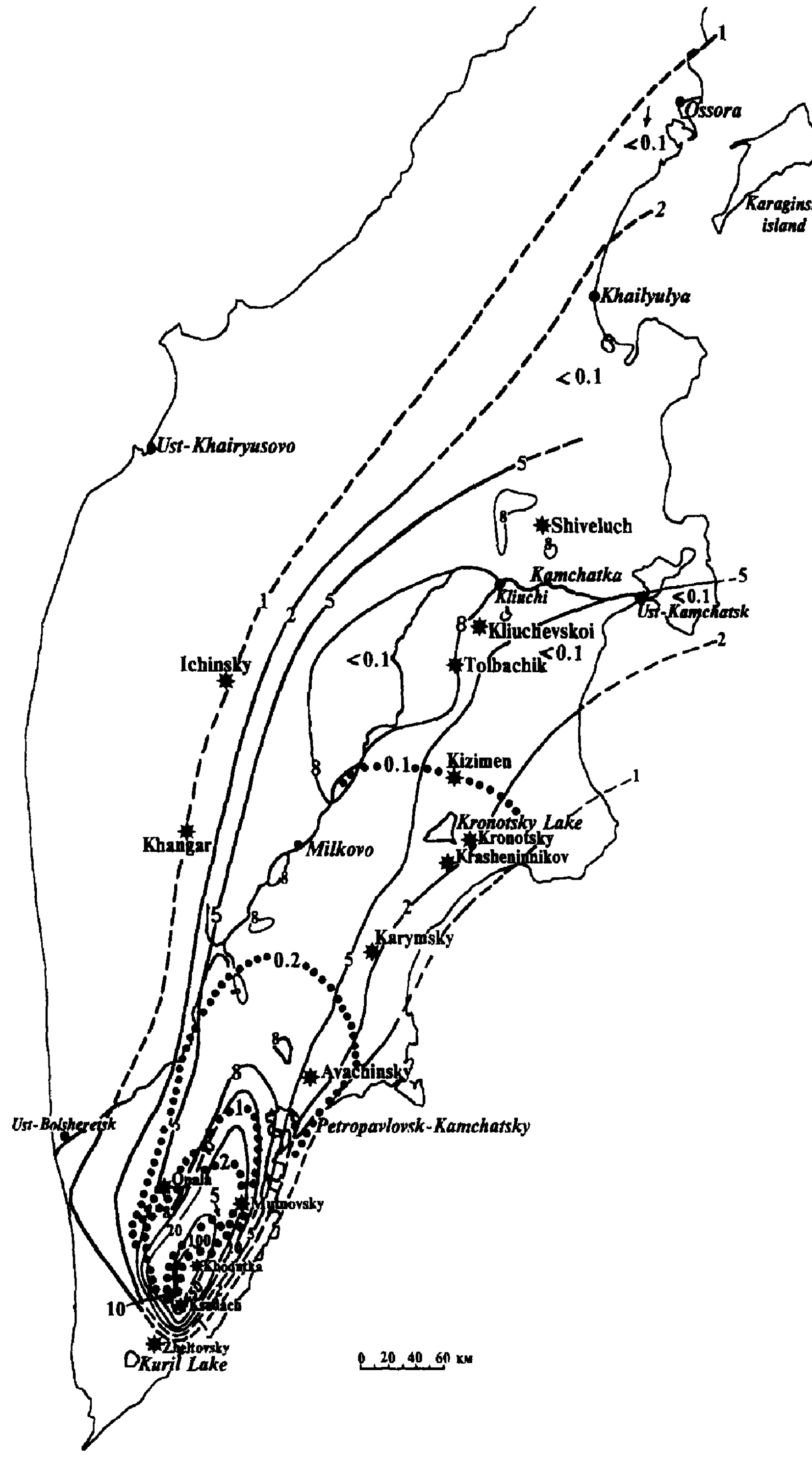


Fig. 2. Isopach (cm) and isopleth (maximum sizes of particles, cm) maps for KS_1 tephra fall. Isopachs, solid and dashed lines; isopleths, large dots.

Teplaya river (Fig. 3, section 8880). Three lower units comprise white porous pumice and the upper unit consists of grey and blue-grey more dense pumice. Thickness of the units ranges from 4 to 12 m. In the central part of the massif near the caldera rim it locally reaches 30–50 m.

Beyond the area of pyroclastic-flow deposits, related ash-cloud surge deposits ("nuee ardente" deposits) have been identified. In sections at a distance of 20–30 km from the volcano (Fig. 3, section 8825) they replace pyroclastic-flow deposits and have the same stratigraphic position. Ash-cloud surge deposits usually are non-stratified and consist of light-colored fine material with a small admixture of coarse grains. In the region of Khodutka volcano, 30 km to the northeast, the thickness of such deposits reaches 4–10 cm.

The basal layer of the KS_1 sequence near the vent is composed of greenish-grey, dusty consolidated (Fig. 3, section 8880), or stratified coarse-grained material with interlayered fine bands (Fig. 3, section 8839). We interpret this as a pyroclastic base-surge deposit, indicating that the KS_1 eruption began with a phreatomagmatic phase, perhaps due to the existence of a lake in former caldera IV.

Proximal tephra falls deposits are pumice lapilli and bombs. At least four bomb beds are identified (Fig. 3, section 8880), each underlying pyroclastic-flow deposits. Pumices of the lower three beds are white or yellow and those of the upper bed are grey or blue-grey. Pumice bombs and lapilli reach 40 cm diameter on the northern part of the caldera rim and 1 cm at a distance of 145 km northeast from the vent (Fig. 2).

The ash-fall axis was directed to the north. The grain size diminishes with distance from the volcano (Fig. 2): at sites near Khodutka volcano, 30 km to the northeast, bombs and lapilli dominate; near Petropavlovsk, 140 km to the northeast, tephra are lapilli and coarse ash; farther still, near Kizimen volcano, 380 km to the northeast, the material is coarse and fine ash; beyond 400 km fine ash dominates. An increase in the fraction of fine (< 0.125 mm) ash with distance is apparent (Figs. 5 and 6).

However, at distal sites more than 400 km from the vent, the ash is almost entirely composed of accretionary lapilli (Moore and Peck, 1962; Walker and Croasdale, 1972) roughly 0.25 mm in size, consisting of numerous small (< 63 μm) glass shards. These accretions present in the KS_1 tephra perturb the manner in which the grain size distribution changes with distance, i.e., the increase in a fraction of particles 0.25–0.125 mm in size due to accretion leads to the bimodal distribution at distances of more than 400 km (Fig. 5).

The isopach map for the tephra (Fig. 2) shows the distinct secondary increase of ash thickness in the north of the Kamchatka River valley, in the region of the Tolbachik plateau and in the region of Shiveluch volcano. Such a phenomenon was reported by Brazier et al. (1983) for the 1980 Mount St. Helens and 1979 Soufriere eruptions, and is obviously the result of the accretionary lapilli formation.

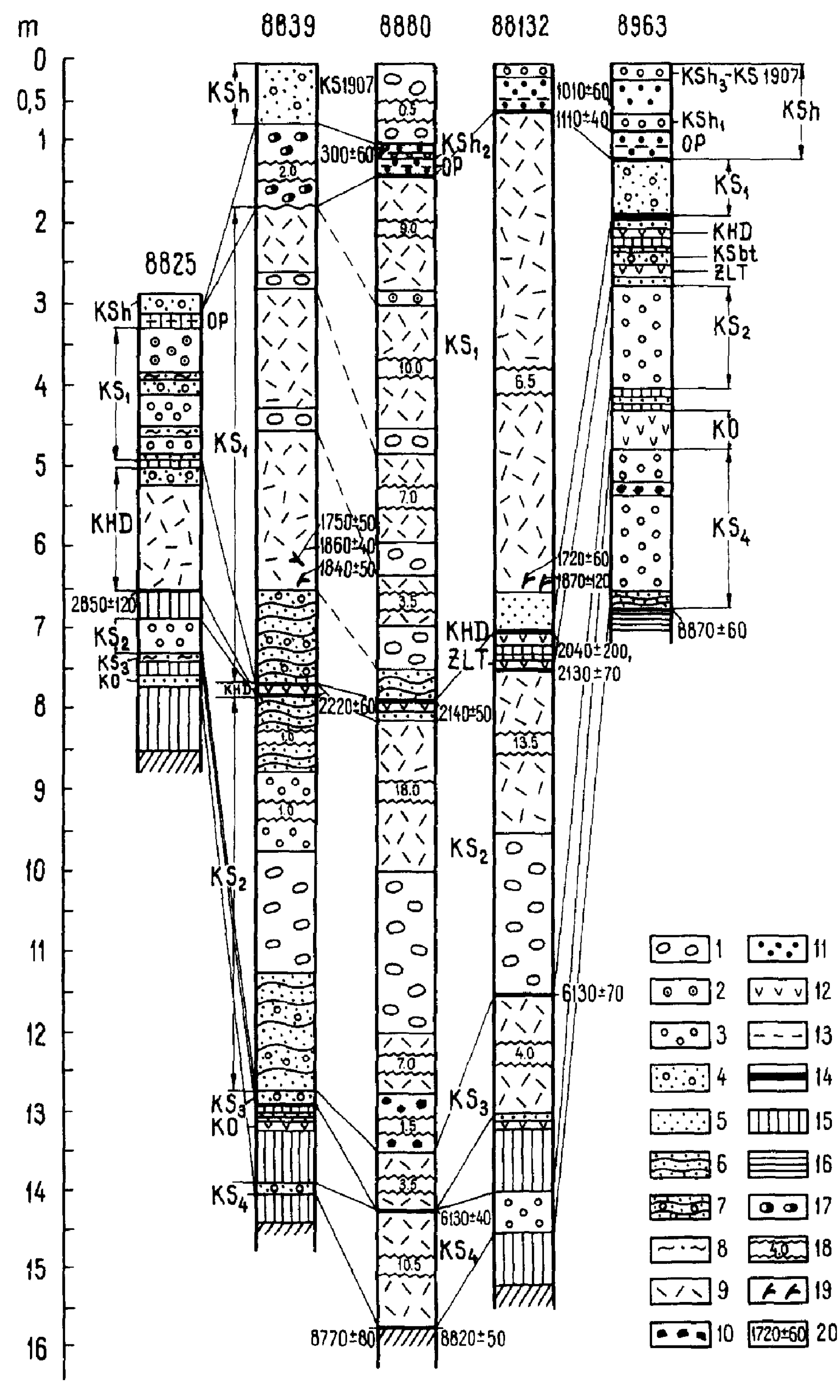
Pumice particles in the tephra have a delicate appearance. Examination by electron microscope revealed that their principal feature is the great number of thin-walled pores oriented in a random way constituting > 80% of the particle volume (Fig. 7).

Within eastern Kamchatka, the KS_1 tephra is a yellow, coarse to fine ash. In the Kamchatka River valley the tephra comprises two layers: yellow coarse or fine ash below, and grey fine ash at the top. These two layers correspond to two packets of pyroclastics at Ksudach volcano: a lower white or yellow packet and an upper grey one.

4. The history of identification and correlation of KS_1 tephra

KS_1 tephra is one of the most important regional marker horizons for Holocene stratigraphy because it covers almost all Kamchatka. We shall discuss the history of identification and correlation of KS_1 tephra within the peninsula since in earlier publications it was given a variety of names attributed to a variety of eruptive centers.

Previously the KS_1 ash in the region of the Kliuchevskoi volcano group and Kliuchi city was described as ash from Shiveluch volcano and designated SH_4 (Piyp, 1948; Menyailov, 1955; Markhinin et al., 1962; Gushchenko, 1965; Dikov, 1969; Braitseva et al., 1984, 1988, 1989b, 1991). This fine ash served as an important marker horizon and was used in tephrochronological studies at Tolbachik, Kliuchevskoi, and Bezymianny volcanoes and during archaeological investigations in the Kamchatka River valley. However, studies of the chemical and mineral compositions of the ash demonstrated that it differed from other ashes of Shiveluch volcano (Geptner and Ponomareva, 1979; Kirianov, 1983; Felitsyn and Kirianov, 1990; Felitsyn et al., 1991). The ash does not contain hornblende, which is common at Shiveluch, has a low K_2O content, and consists nearly



entirely of volcanic glass, which suggests a distant source. Later we obtained new data confirming that neither the grain size nor thickness of this ash increased toward Shiveluch.

During tephrochronological studies in southern and eastern Kamchatka, a tephra horizon KHD was recognized and attributed at the time to Khodutka volcano (Fig. 2), for its thickness (2–4 m) and clast size (bombs up to 10–15 cm) were very large there (Kirsanova and Melekestsev, 1988; Melekestsev and Kirianov, 1988; Braitseva et al., 1989a; Melekestsev et al., 1990). Its thickness gradually decreases to the north of Khodutka volcano. In the region of Kronotsky lake and Kizimen volcano, the coarse ash from this horizon was seen to lie directly above the fine ash SH_4. The composition of ash SH_4 was found to be similar to that of KHD (Kirianov et al., 1990). Later tracing and correlation of ashes in southern Kamchatka let us see that ash KHD was produced by the Ksudach caldera-forming eruption (KS_1) because its thickness and clast sizes increase towards a maximum at this volcano. We studied the KS_1 erupted products near Ksudach and obtained new data on their composition and ages.

At the same time, in the valley of the Kamchatka River, we identified a fine grey ash that lies directly above layers KHD and SH_4 and whose composition was similar to that of these ashes. Its source remained unknown.

Ultimately we reinterpreted all the evidence accumulated, using data from direct tracing of ashes, their composition and their ages. Based on these data, we concluded that all of the described ash beds —KHD, SH_4 and the grey ash in the Kamchatka River valley—are products of the same Ksudach caldera-forming eruption KS_1. The ash exhibits regular decreasing grain size with distance from the source, from the proximal coarse tephra "KHD" to the distal fine ash "SH_4". The progressive decrease of tephra thickness is somewhat complicated by its secondary thickening in the region of the Kliuchevskoi volcano group. The composition of all the tephra corresponds universally to that of pyroclastics from Ksudach volcano. The position of grey ash in the upper tephra horizon in the Kamchatka River valley is consistent with the stratigraphic position of the grey pumice deposits in the upper part of the sequence at Ksudach volcano. Grey ash was not found within eastern Kamchatka, which is interpreted to result from a shift of ash dispersal axes for "yellow" and "grey" tephra.

5. Composition of products

The major component of KS_1 tephra is volcanic glass. It dominates in lapilli and bombs (97%) and in fine ash (93%). In coarse ash the volcanic glass content decreases to 80–85% because of increasing crystal content (Fig. 8) due to eolian differentiation. The mineral assemblage of erupted products comprises plagioclase, ortho- and clinopyroxene, and titanomagnetite. Hornblende is lacking.

Bombs and lapilli near the vent are low-potassium rhyodacites (Fig. 9). Their composition remained constant during the KS_1 eruption (Fig. 10). Both white and grey pumice bombs and lapilli at Ksudach and yellow and grey fine ash at distal localities do not differ in composition (Table 2) and contain from 68 to nearly 72% SiO_2. Coarse ash, which fell at

Fig. 3. Position of KS_1 deposits in a pyroclastic sequence of Ksudach volcano. Tephra (*1–5*): *1* = bombs and lapilli of white to yellow pumice; *2* = bombs and lapilli of blue-grey pumice in the KS_1 pyroclastics; *3* = lapilli; *4* = coarse ash and lapilli; *5* = coarse ash. Pyroclastic surge deposits (*6–8*): *6* = stratified coarse ash; *7* = stratified coarse ash with lapilli; *8* = fine ash of pyroclastic surges from ash clouds; *9* = pyroclastic-flow deposits; *10* = explosion breccia; *11* = pyroclastics from Shtyubel cone; *12* = tephra from other volcanoes; *13* = marker tephra layer from Opala volcano (not to scale); *14* = buried soils; *15* = sandy loams; *16* = lacustrine deposits; *17* = lahar deposits; *18* = discontinuity of layer thickness in meters; *19* = wood and charcoal; *20* = radiocarbon dates. KS_1, KS_2, KS_3, KS_4, deposits of caldera-forming eruptions from Ksudach volcano. *KSbt* = "bomb tuff" from Ksudach volcano. *KSh* = pyroclastics from Shtyubel cone; KSh_1, KSh_2, KSh_3 = tephra from the largest eruptions from Shtyubel cone. Tephra marker beds: *OP*, from Opala volcano (Baraniy Amphitheater) 1500–1400 yr B.P.; *KHD*, from Khodutka volcano (Khodutkinsky "maar") 2800 yr B.P.; *ZLT*, from Zheltovsky volcano 5000 yr B.P.; *KO*, eruptions associated with formation of Kuril Lake–Iliinsky caldera (7700–7600 yr B.P.). Sections locations are shown in Fig. 4. Section 8825 is located at Khodutka volcano 30 km north of Ksudach volcano.

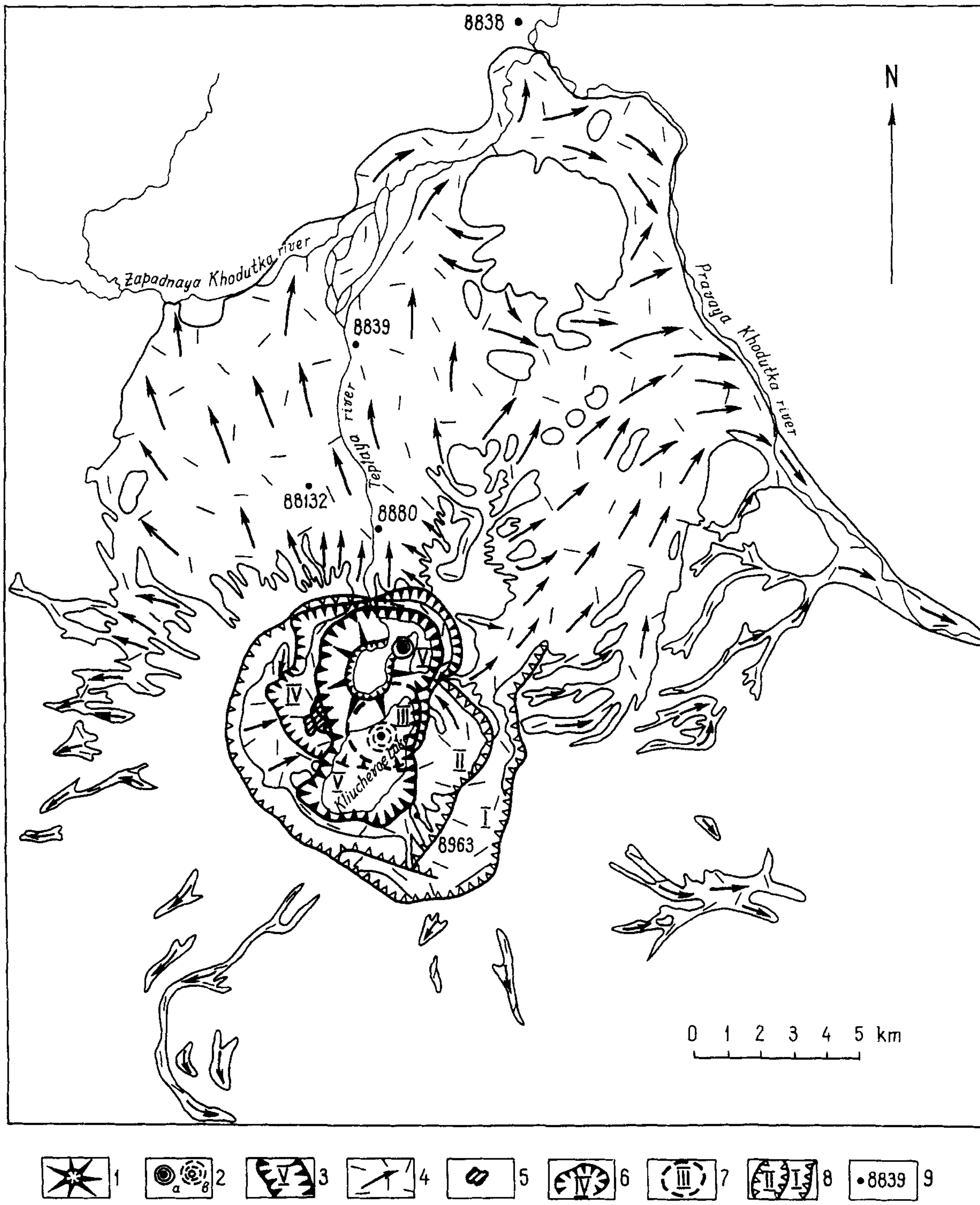


Fig. 4. Pyroclastic flows KS_1 and position of caldera V. *1* = Shtyubel cone and its crater; *2* = post-caldera extrusive domes in caldera V, *a* established, *b* presumed; *3* = caldera *V* scarp; *4* = KS_1 pyroclastic flows; *5* = post-caldera extrusive domes (Paryashchiy Utes, etc.) in caldera *IV*; *6* = caldera *IV* scarp; *7* = presumed position of caldera *III*; *8* = scarp edges of Late Pleistocene calderas *I* and *II*; *9* = numbers of sections shown in Fig. 3. *8639* and *8839* are the numbers of the same section measured twice.

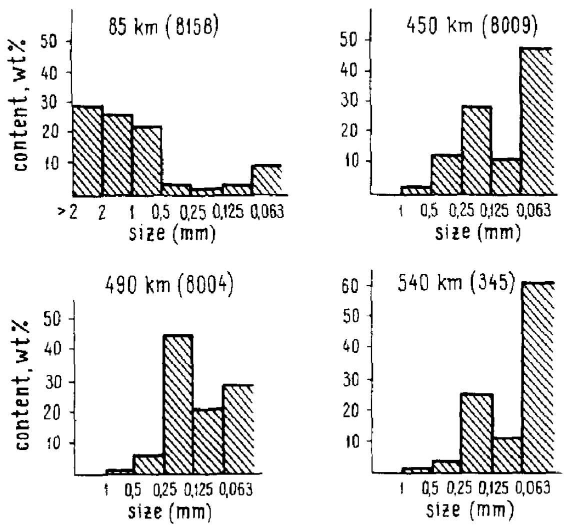


Fig. 5. Histograms of grain size distribution for KS_1 tephra at different distances from the eruptive center. Numbers of sections are bracketed. For sections locations see Fig. 6.

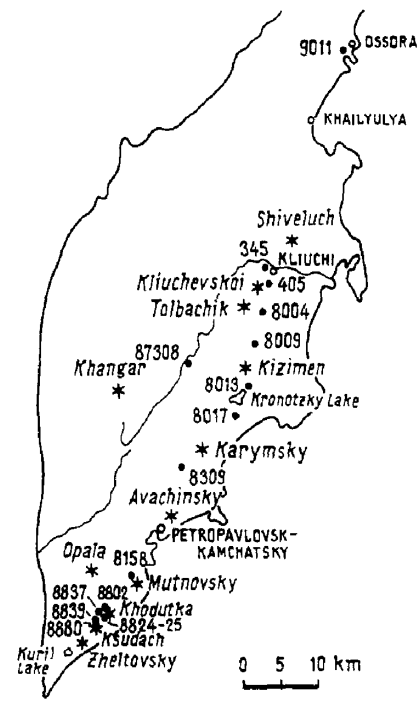


Fig. 6. Locations of sections for which grain size (Fig. 5), chemical (Table 2) and mineral (Fig. 8) compositions of KS_1 pyroclastics are given. *8639* and *8839* are the numbers of the same section measured twice.

some distance from the volcano (Figs. 2 and 9), is more mafic and contains from 63 to 68% SiO_2 as a result of its enrichment in minerals due to eolian differentiation (Fig. 8). The most distal ash sample, in Ossora village at 900 km distance, has the highest SiO_2 content, 73.72%; this sample consists nearly entirely of volcanic glass. Thus, lateral variations in composition of KS_1 ash related to eolian gravitational differentiation are compatible with regular trends obtained for other Kamchatkan ashes (Kirianov and Solovyova, 1991). Notwithstanding the fact that SiO_2 contents of ashes range by 11%, all the sam-

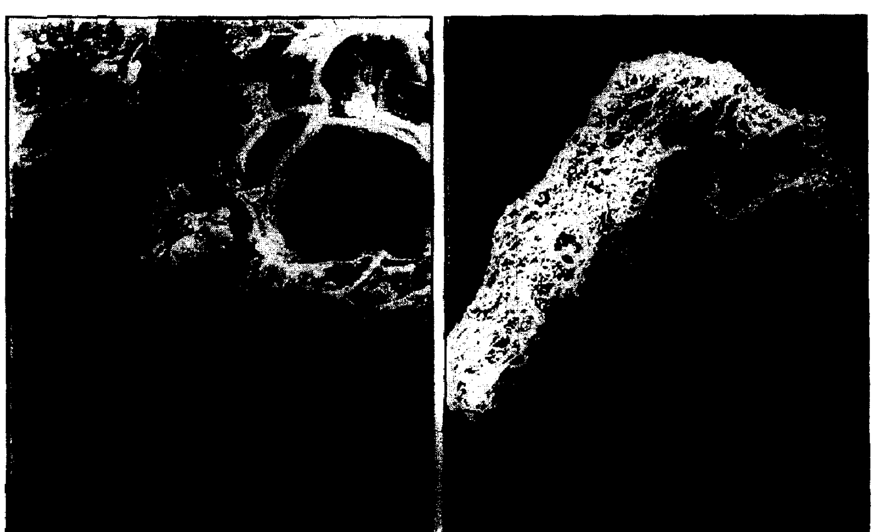


Fig. 7. Surface of a pumice particle from KS_1 tephra under scanning electron microscope. Left ×2020; right ×130.

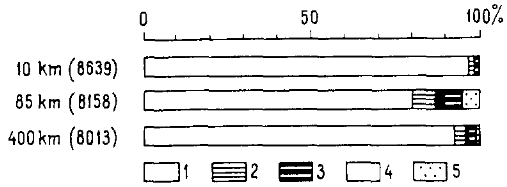


Fig. 8. Mineral composition of KS_1 tephra-fall deposits at different distances from the eruptive center: 10 km—lapilli and bombs; 85 km—dominantly coarse ash; 400 km—dominantly fine ash. *1* = volcanic glass; *2* = plagioclase; *3* = rock fragments and altered minerals; *4* = magnetite; *5* = pyroxenes. Numbers of sections are bracketed.

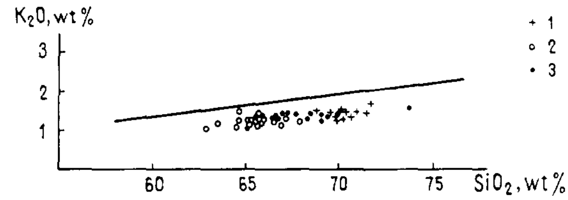


Fig. 9. Classification diagram for KS_1 pyroclastic deposits. Upper boundary of the field of low-K rocks after Gill (1981). *1* = bombs and pumice lapilli; *2* = dominantly coarse ash; *3* = dominantly fine ash.

ples fall into the field of low-potassium rocks, forming a swarm of points parallel to its upper boundary defined by Gill (1981) (Fig. 9).

Studies of the composition of KS_1 tephra throughout Kamchatka made it possible to determine its characteristic features helpful for identification and correlation of this excellent marker horizon. These features are: (1) SiO_2 contents 63–74%; (2) low potassium content; and (3) lack of hornblende. These criteria combined with data on ages are sufficient to discriminate KS_1 tephra from Shiveluch, Opala and Khodutka ashes that are close to KS_1 tephra stratigraphically and in SiO_2 abundance (Braitseva et al., 1992, 1994).

6. The collapse caldera

Collapse caldera V formed as a result of the KS_1 eruption (Figs. 1 and 4). Its boundaries are defined by the limits of KS_1 deposits, which do not crop out inside the caldera. The southern part of the caldera coincides with caldera III-1 recognized by Selyangin (1990). However, we regard it as including also the

Table 2
Representative analyses of products from the Ksudach eruption KS_1

Components	Bombs and pumice lapilli			Coarse ash			Fine ash		
	White, yellow from lower unit		Grey from upper unit				Pale-yellow		Grey
	8880/5	8637/15	8802/2	8824/2	8309/3	8017/1	405/15	9011/2	87308/2
SiO_2	71.78	69.73	70.09	62.86	65.20	67.90	68.34	73.72	69.89
TiO_2	0.55	0.67	0.59	1.06	0.76	0.62	0.48	0.69	0.61
Al_2O_3	14.68	14.98	15.08	15.03	17.24	16.04	15.77	14.60	14.67
Fe_2O_3	0.59	1.67	0.55	3.00	1.78	0.87	1.70	2.87[a]	1.12
FeO	2.53	2.72	3.24	5.43	3.88	3.59	2.65	–	2.69
MnO	0.14	0.09	0.15	0.14	0.18	0.14	0.14	0.08	0.15
MgO	0.87	0.44	1.11	1.88	1.51	1.40	1.35	0.54	1.07
CaO	2.29	3.35	2.87	5.79	4.20	3.42	3.82	1.09	3.92
Na_2O	4.91	4.83	4.82	3.58	3.85	4.60	4.31	4.67	4.36
K_2O	1.57	1.42	1.41	1.05	1.15	1.23	1.32	1.52	1.38
P_2O_5	0.10	0.09	0.10	0.17	0.26	0.18	0.12	0.22	0.14
L.O.I.	5.08	1.82	4.27	8.01	6.85	6.40	4.00	46.25	2.73
Total	99.56	100.34	99.58	99.68	99.74	99.75	99.55	99.55	100.10

Analyses were made at the Chemical Laboratory of the Institute of Volcanology by "wet" chemical method. Analyses were recalculated water and organic matter free. L.O.I.(loss on ignition) and original analytical totals are listed under the line.
[a] total FeO as Fe_2O_3.

area where the Shtyubel cone is presently located. Earlier Melekestsev (Melekestsev and Sulerzhitsky, 1990) described only this northern part as caldera V. In this area, particularly to the north and east, caldera V corresponds closely in position with caldera IV, which surrounds it. The boundary of caldera V is defined by scarps west and east of the lake, and in the southwest its scarp bounds the Paryashchiy Utes (Steaming Rock) extrusion. This scarp cannot belong to caldera IV for the following reasons.

Tephrochronological studies have shown that the volcanic massif, consisting of a series of extrusions —including Paryashchiy Utes (Fig. 4)—is not of Late Pleistocene age, as was previously considered, but is substantially younger. Lavas of this massif are overlain only by KS_1 pyroclastics; no other more ancient pyroclastics, including KS_2 and KS_3 are present on them. Consequently, these extrusions formed after the KS_2 eruption and formation of caldera IV. They are somewhat younger than 6000 yr B.P., and this is the reason why the Paryashchiy Utes retains heat and is actively steaming. Thus, this massif is interpreted to be a series of post-caldera extrusions within caldera IV. Then the pronounced scarp bounding the Paryashchiy Utes is part of the caldera V boundary (Fig. 4).

The caldera is 4 × 6.5 km in diameter and has an area of 19 km^2 within the rim; it is 4 × 5.5 km and

Table 3
Radiocarbon dates for eruption deposits KS_1

Date	Sample No.	Area of sampling	Material for dating
1720 ± 60 *	GIN-2959a	Ksudach volcano	charcoal [a]
1750 ± 5 *0	GIN-2975a	Ksudach volcano	wood [a]
1840 ± 50 *	GIN-2974	Ksudach volcano	charcoal [a]
1860 ± 40 *	GIN-2975b	Ksudach volcano	wood [a]
1870 ± 120 *	GIN-2959b	Ksudach volcano	charcoal [a]
1690 ± 80 *	GIN-6321	Yar Cherny, Kamchatka River	peat over ash KS_1
1780 ± 40 *	IVAN-191	Karymsky volcano	soil over ash KS_1
1800 ± 200 *	IVAN-328	Uzon caldera	soil over ash KS_1
1660 ± 70 *	IVAN-397	Petropavlovsk-Kamchatsky city	peat under ash KS_1
1690 ± 190 *	IVAN-705	Sharomy village	peat under ash KS_1
1820 ± 120 *	IVAN-450	Yar Cherny	peat under ash KS_1
1860 ± 40 *	IVAN-193	Karymsky volcano	soil under ash KS_1
1860 ± 60 *	GIN-1356	Valley of Paratunka River	soil under ash KS_1
1860 ± 150 *	IVAN-331	Uzon caldera	soil under ash KS_1
1890 ± 80 *	IVAN-639	Avachinsky volcano	peat under ash KS_1
1920 ± 50	GIN-2991	Khodutka volcano	peat under ash KS_1
1950 ± 60	IVAN-556	Yar Cherny	soil under ash KS_1
2050 ± 50	GIN-1180	Petropavlovsk-Kamchatsky city	peat under ash KS_1
2040 ± 200	GIN–2980	Ksudach volcano	soil under pyroclastic-flow deposits
2130 ± 70	GIN-2959	Ksudach volcano	soil under pyroclastic-flow deposits
2140 ± 50	GIN-2985	Ksudach volcano	soil under pyroclastic-flow deposits
2220 ± 60	GIN-2976	Ksudach volcano	soil under pyroclastic-flow deposits
2200 ± 90	GIN-1853	Karymsky volcano	soil under ash KS_1
2020 ± 90	IVAN-70	Tolbachik plateau	soil under ash KS_1
2240 ± 40	IVAN-36	Tolbachik plateau	wood from soil over ash KS_1
2060 ± 50	GIN-1852	Tolbachik plateau	charcoal in soil under ash KS_1
2070 ± 120	IVAN-57	Tolbachik plateau	charcoal in soil under ash KS_1
2440 ± 50	IVAN-82	Tolbachik plateau	soil under ash KS_1
2460 ± 100	IVAN-55	Tolbachik plateau	soil under ash KS_1
2080 ± 100	IVAN-132	Kliuchevskoi volcano	soil under ash KS_1
2040 ± 80	IVAN-121	Kliuchevskoi volcano	charcoal in soil under ash KS_1

The table contains all the dates on charcoal and wood, but for the soils and peat only the values of the oldest extracts from the layers overlying the ash horizon and those of the youngest extracts from underlying layers (see Fig. 11), since they define the age of ash. The dates used for the calculation of the average age are marked with an asterisk.
[a] Material from pyroclastic-flow deposits.

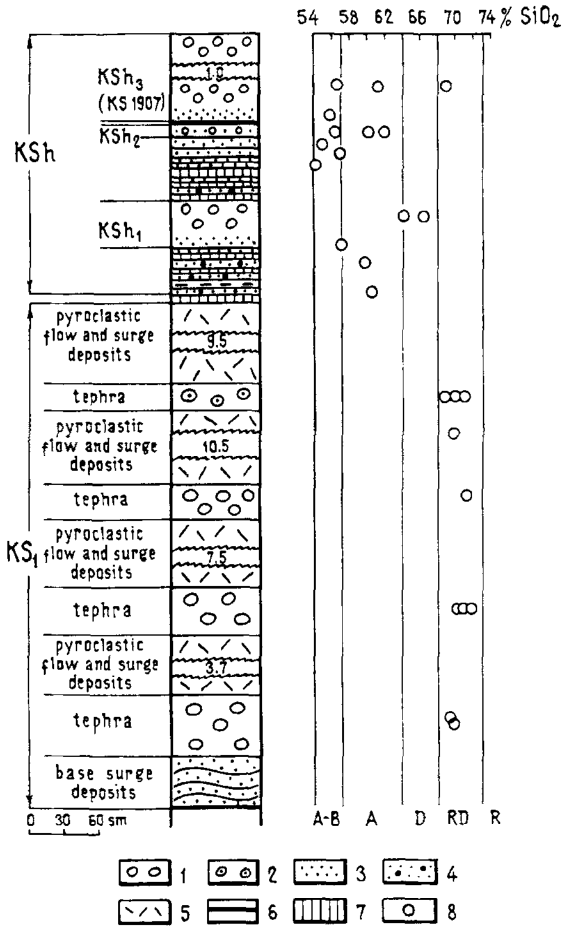


Fig. 10. Deposit sequence for eruption KS_1 and formation of Shtyubel cone. *1* = bombs and lapilli of light-colored pumice; *2* = lapilli of blue-grey pumice; *3* = coarse ash; *4* = coarse ash with lapilli; *5* = pyroclastic-flow and -surge deposits; *6* = buried soil horizons; *7* = sandy loams; *8* = SiO_2 content of pyroclastic material. For other symbols see Fig. 3.

15 km^2 in area at the bottom. The volume of its cavity down to lakes Kliuchevoe and Shtyubel is about 4.5 km^3, and if we take into account the volumes of the lakes and post-collapse volcanic fill the original volume of the caldera cavity may be 6.5–7 km^3.

7. The age

At present about 30 ^{14}C dates are available for KS_1 deposits at the volcano and at different distances from it (Table 3; Fig. 11). Dates ranging from 1870 to 1720 yr B.P. have been obtained on charcoal and wood in pyroclastic-flow deposits near the caldera. Dates obtained on the soil and peat underlying the KS_1 tephra range from 2400 to 1660 yr B.P. The younger of them (1890–1660 yr B.P.) are in good agreement with the above-mentioned dates on charcoal and wood. The soils below KS_1 tephra (sections 1, 4 and 6 in Fig. 11) that give older ages (2200–2000 yr B.P.), must have been formed over a long period of time, with the dates obtained reflecting the mean age of the whole soil horizon. Dates ranging from 1800 to 1690 yr B.P. on the soil and peat overlying KS_1 tephra (Fig. 11) also indicate that the eruption took place at 1800–1700 yr B.P.

We note that dates in sections 8 and 9 differ somewhat. Dates of about 2000 yr B.P. and older have been obtained here on soils not only underlying the ash, but also overlying it, as well as on charcoals and wood. At the Kliuchevskoi volcano group the age of this ash, called previously SH_4, was determined to be roughly 2000 yr B.P. (Braitseva et al., 1988). However, outside the Kliuchevskoi volcano group farther northeast we again obtain dates of 1800–1700 yr B.P. for the same ash (section 10). The older ages of the charcoal and wood could be explained by old wood trees that died a few hundred years before the eruption. The reason for the older ages of the soils overlying the ash in the region of the Kliuchevskoi volcano group remains obscure.

We determined the weighted average age and calendric age of the KS_1 eruption from the technique of Stuiver and Reimer (1993). For the calculations we used the dates on charcoal, wood, and thin soil and peat layers. Dates from thick soil layers were used only in cases where data were obtained on successive alkaline extracts (technique of Sulerzhitsky, see Braitseva et al., 1993), in which case we used the younger dates for the soil underlying and the older dates for the soil overlying the tephra. The dates used in the calculation are starred in Table 3. The weighted average radiocarbon age calculated from these fifteen dates is 1806 ± 16 yr B.P. that corresponds to calibrated age A.D. 147(236)317 ($\pm 2\sigma$).

8. The volume of erupted products

The KS_1 eruption produced the greatest volume of erupted material (Table 1) of all the caldera-forming eruptions from Ksudach. Tephra-fall deposits dominated the eruption products.

The contours and the area of the ash-fall zone, and consequently, the fall deposit volume, cannot be defined precisely because great amounts of ash fell over the sea. Even on land it is difficult to reconstruct the boundaries of the ash-fall zone outside the 1-cm isopach, because no distinctive tephra layers were preserved there. Based on the isopach map (Fig. 2) the area and the volume of tephra-fall deposits inside the 1-cm isopach may be roughly estimated to be 300,000 km^2 and 13 km^3, respectively. By analogy with a smaller (tephra volume 1.5–2 km^3), but similar Plinian eruption of Ksudach in 1907, when the ash fell over an area of about 1,000,000 km^2, one may propose that the area of ash fall during the KS_1 caldera-forming eruption was a few millions of square kilometers as estimated for

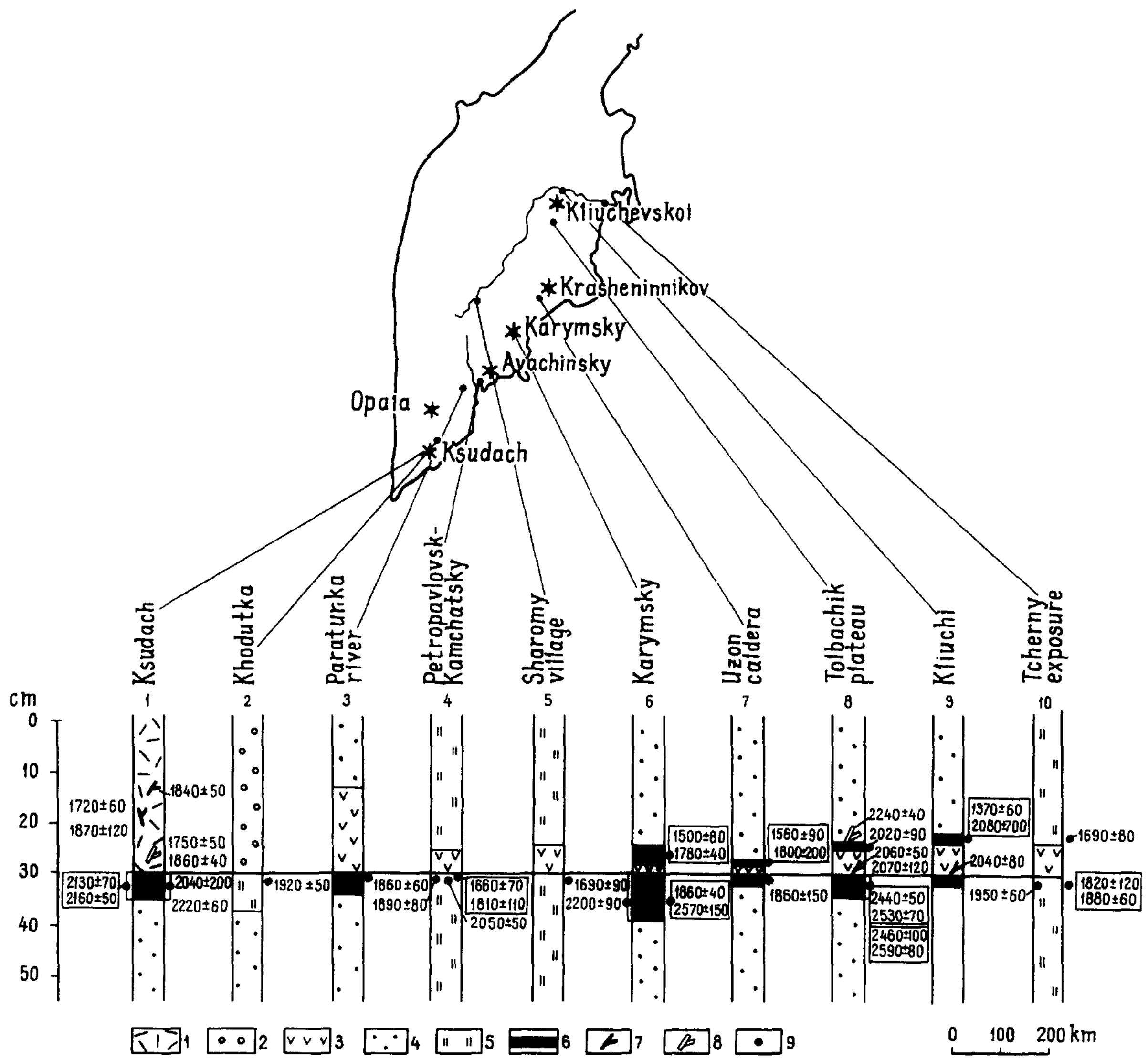


Fig. 11. ^{14}C dates for KS_1 eruption deposits. *1* = pyroclastic-flow deposits; *2* = pumice lapilli; *3* = coarse and fine ash; *4* = deposits of soil-pyroclastic sequence; *5* = peat; *6* = buried soils; *7* = charcoal; *8* = wood; *9* = position of samples dated. In the boxes are dates for successive alkaline extracts from the same soil sample.

both the eruptions of Krakatau in 1883 (3,800,000 km^2; Simkin and Fiske, 1983) and Quizapu, in Chile, in 1932 (5,000,000 km^2; Casertano, 1965; Hildreth and Drake, 1992). If we assume that ash from the KS_1 eruption fell in an area of 2,000,000 or 3,000,000 km^2, then the total volume of tephra was at least 14–15 km^3. Since at the distal edges of the surge deposits, it is difficult to discriminate tephra-fall from pyroclastic-surge deposits, the latter are included in the volume of tephra fall.

Pyroclastic flows of the KS_1 eruption were also the most voluminous at Ksudach in the Holocene. The reconstruction has shown that they covered roughly 200 km^2 with a volume of 3 km^3 (the mean thickness of deposits was 15 m) outside the caldera. We propose also that no less than 1 km^3 of pyroclastic-flow deposits was deposited inside the 19-km^2 caldera with a mean thickness of about 50 m. Then, we can estimate the total volume of pyroclastic-flow deposits to be about 4 km^3.

Thus, the total volume of eruption products may have been of the order of 18–19 km^3 or about 8 km^3 DRE (calculated for dense rock at 2.3–2.4 g/cm^3, and pumiceous material at 1–1.1 g/cm^3). This value is in good agreement with the volume of the cavity of caldera V (6.5–7 km^3).

9. The course of the eruption

The KS_1 eruption produced great amounts of tephra (Table 4). The course of the eruption has been reconstructed from the sequence of deposits (Fig. 10). The eruption began as phreatomagmatic with the formation of typical pyroclastic base surges. It is worth noting that the KS_1 eruption began with the ejection of juvenile material whereas some other eruptions from Ksudach (KS_2, KS_3) began with violent explosions, destroying substratum and forming a layer of explosion breccia. Then the explosive process became rhythmic (cyclic). At least four cycles are recognized. Each cycle began with tephra falls and finished with pyroclastic-flow emplacement. In the course of the KS_1 eruption the proportion of juvenile material remained extremely high; lithics occur only in pyroclastic-flow deposits.

The height of the eruptive column was determined to be 23 km (Bursik et al., 1993). Further refinement has yielded column heights in the range of 22–30 km (M. Bursik, pers. commun.). The ash-fall axis was directed to the north along the valley of the Kamchatka River (Fig. 2). The axis was shifted somewhat eastward at the beginning (yellow ash) and westward at the end (grey ash) of the eruption. The isopach pattern shows that at the latitude of the Kliuchevskoi volcano group and Shiveluch the ash cloud axis turned eastward to the ocean, which appears to have resulted from changing wind directions.

Pyroclastic flows moved down all flanks of the volcano except in the southern sector, where the high rims of the older calderas screened them.

Immediately after the caldera formed, a small extrusive dome (Fig. 4) grew inside it. According to bathymetric data reported by S.M. Fazlullin (pers. commun.) an analogous dome seems to exist at the bottom of Kliuchevoe lake, which has filled the caldera depression.

10. Post-caldera activity

In a short period of time (no more than 100 years) the Shtyubel stratovolcano started to form within the caldera (Braitseva et al., 1994). Its products are basaltic andesite and andesite with SiO_2 in the range 54–62% (Fig. 10). Three large explosive eruptions occurred from the Shtyubel stratovolcano: 1000–1100 yr B.P. (KSh_1), 300 yr B.P. (KSh_2) and in 1907 (KSh_3). The volumes of tephra erupted were,

Table 4
Characteristics of caldera-forming eruption KS_1, Ksudach, caldera V

Volume of fall deposits (km^3)	Volume of pyroclastic-flow deposits (km^3)	Total volume (km^3)	Volume recalculated DRE (km^3)	Height of eruptive column (km)	Caldera size (km)	Volume of caldera cavity (km^3)
14–15	4	18–19	8	23	4 × 6.5	6.5–7

respectively, 1, 0.4–0.5 and 1.5–2 km^3, and the heights of eruptive columns were > 15 km, > 10 km and as high as 22 km (Bursik et al., 1993). At Ksudach, tephra layers from the KSh_1 and KSh_3 eruptions are distinctly zoned: the lower portions of each contain black basaltic andesite lapilli or coarse ash with 54–56% SiO_2, and the upper portions consist of light-colored pumice bombs and lapilli with 56–66% SiO_2. Banded varieties are abundant among pumice bombs of both eruptions. The SiO_2 contents of adjacent bands differ by 6–8% (Volynets, 1979a).

These compositional variations in the Ksudach erupted products suggest that the KS_1 eruption may have been triggered by injection of hot mafic magma into a cooler silicic magma reservoir (Sparks and Sigurdsson, 1977; Volynets, 1979b). During the KS_1 eruption, magma was ejected from the uppermost, silicic portion of the reservoir. More mafic magma came to the surface later, during formation of the Shtyubel Cone (Fig. 10).

11. Environmental impact

The volume of erupted products for KS_1 (18–19 km^3) exceeds that for any eruption of our era not only in Kamchatka, but also within the 4000-km northwestern portion of the Ring of Fire, including Japan, the Kurile Islands and Kamchatka. Such a volume of erupted material ranks the KS_1 eruption with the well-known eruptions of Krakatau in 1883 (17–21 km^3; Self and Rampino, 1981) and Katmai/Novarupta in 1912 (17 km^3 of tephra; Fierstein and Hildreth, 1992). The height of the KS_1 eruptive column (22–30 km) is comparable with that of Novarupta (17–26 km). The KS_1 eruption may therefore have greatly affected the atmosphere as did the Krakatau and Katmai eruptions, and the Ksudach eruption of 1907 (Hulten, 1924; Lamb, 1970).

The Ksudach 1907 eruption produced a moderate acidity peak in the Greenland ice (Hammer et al., 1980). The volume of the KS_1 eruption exceeds by an order of magnitude that of the 1907 eruption from Shtyubel Cone and is comparable with those of the Krakatau and Katmai eruptions, which produced distinct acidity peaks in the Greenland ice. Based on this observation, the KS_1 eruption should also be represented by an acidity peak. Unfortunately, no data are available in the Crete and Camp Century cores for the interval A.D. 147–317 when the KS_1 eruption must have occurred (Hammer et al., 1980). Data for the GISP2 ice core (Zielinski et al., 1994) suggest that five peaks in SO_4^{2-} concentration (A.D. 152, 161, 181, 264 and 267) fall into this interval. We think it more likely that either the A.D. 264 or the A.D. 267 peak was caused by the KS_1 eruption as they are closer to average age A.D. 236.

The voluminous KS_1 eruption was probably an ecological catastrophe for Kamchatka, due to dispersal of tephra mainly along the peninsula. The minimum area of total devastation coinciding with pyroclastic-flow deposits and heavy tephra fallout is about 400–500 km^2 (following the 40-cm isopach of Fig. 2). Vegetation was also adversely affected over an additional area of about 12,000 km^2 where ash thickness was 5–40 cm. Only outside the 5-cm isopach might the vegetation have benefited from the ash as a source of useful trace elements.

12. Conclusions

(1) The latest caldera-forming eruption from Ksudach (KS_1), which occurred about A.D. 240, was the greatest eruption of our era in the Kurile–Kamchatka region: the volume of pyroclastics was 18–19 km^3, of which 14–15 km^3 was from tephra falls. The height of the eruptive column reached 22–30 km. As a result of this eruption, a collapse caldera (caldera V) with a size of 4 × 6.5 km and a cavity volume of 6.5–7 km^3 was formed.

(2) The eruption began as phreatomagmatic with the formation of pyroclastic surges. Later the process became rhythmic: repeated tephra falls were followed by the formation of pyroclastic flows extending outward for 20 km. Tephra was dispersed northward to a distance of more than 1000 km. The composition of erupted products was rhyodacite, remaining unchanged during the eruption. Only in the post-caldera stage, during the formation of Shtyubel Cone within the caldera was more mafic material supplied to the surface.

(3) The injection of more mafic melt into a felsic magma chamber and the mixing of magmas with

different compositions may have been the triggering mechanism for the eruption.

(4) The characteristics of the KS_1 eruption are comparable with those of the 1883 Krakatau eruption. The eruption may have affected the climate and produced an acidity peak in the Greenland ice.

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