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Holocene Key-Marker Tephra Layers in Kamchatka, Russia

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Detailed tephrochronological studies in Kamchatka Peninsula, Russia, permitted documentation of 24 Holocene key-marker tephra layers related to the largest explosive eruptions from 11 volcanic centers. Each layer was traced for tens to hundreds of kilometers away from the source volcano; its stratigraphic position, area of dispersal, age, characteristic features of grain-size distribution, and chemical and mineral composition confirmed its identification. The most important marker tephra horizons covering a large part of the peninsula are (from north to south; ages given in ^{14}C yr B.P.) SH_2 (≈1000 yr B.P.) and SH_3 (≈1400 yr B.P.) from Shiveluch volcano; KZ (≈7500 yr B.P.) from Kizimen volcano; KRM (≈7900 yr B.P.) from Karymsky caldera; KHG (≈7000 yr B.P.) from Khangar volcano; AV_1 (≈3500 yr B.P.), AV_2 (≈4000 yr B.P.), AV_4 (≈5500 yr B.P.), and AV_5 (≈5600 yr B.P.) from Avachinsky volcano; OP (≈1500 yr B.P.) from the Baraniy Amfiteatr crater at Opala volcano; KHD (≈2800 yr B.P.) from the "maar" at Khodutka volcano; KS_1 (≈1800 yr B.P.) and KS_2 (≈6000 yr B.P.) from the Ksudach calderas; $KSht_3$ (A.D. 1907) from Shtyubel cone in Ksudach volcanic massif; and KO (≈7700 yr B.P.) from the Kuril Lake-Iliinsky caldera. Tephra layers SH_5 (≈2600 yr B.P.) from Shiveluch volcano, AV_3 (≈4500 yr B.P.) from Avachinsky volcano, OP_{tr} (≈4600 yr B.P.) from Opala volcano, KS_3 (≈6100 yr B.P.) and KS_4 (≈8800 yr B.P.) from Ksudach calderas, $KSht_1$ (≈1100 yr B.P.) from Shtyubel cone, and ZLT (≈4600 yr B.P.) from Iliinsky volcano cover smaller areas and have local stratigraphic value, as do the ash layers from the historically recorded eruptions of Shiveluch (SH_{1964}) and Bezymianny (B_{1956}) volcanoes. The dated tephra layers provide a record of the most voluminous explosive events in Kamchatka during the Holocene and form a tephrochronological timescale for dating and correlating various deposits.

INTRODUCTION

The traces of instantaneous catastrophic events spread over a vast area offer the possibility of providing precise correlation of certain stratigraphic levels in various depositional successions. Their ages being determined, they become excellent time markers and can be used in geochronological investigations. Tephra (volcanic ash) horizons are among the best marker beds of this kind.

Tephra layers are widely spread in Kamchatka Peninsula, which hosts more than 20 active volcanoes. Holocene ash layers separated by soils, sandy loams, or peats form the soil-pyroclastic cover (Fig. 1) that blankets most of Kamchatka. It is a few tens of centimeters thick in areas distant from the active volcanoes and increases up to several meters at their foot. This cover provides a continuous record of the explosive eruptions during the Holocene, while earlier ash layers in Kamchatka were almost everywhere destroyed during Late Pleistocene glaciation and occur as isolated beds.

Tephrochronological studies in Kamchatka allowed us to identify 15 Holocene key-marker tephra layers of regional stratigraphic value and 9 important local marker ash layers. Identification of tephra sources was possible due to preliminary studies that included detailed mapping of the Holocene eruptive centers (Melekestsev *et al.*, 1974) and investigations of geochemical types and petrology of Late Cenozoic volcanic rocks (Volynets, 1994). These data allowed us to identify the eruptive centers that were likely to have produced voluminous explosive eruptions during the last 10,000 years and to determine the characteristic geochemical features of their deposits. Our first results for some of the voluminous ash layers in Kamchatka were published in Braitseva *et al.* (1989b, 1992b, 1995), but these data have been revised and supplemented in the past few years. This paper presents the first detailed account of most Holocene key-marker ash layers in Kamchatka, which form a detailed timescale for its stratigraphy.

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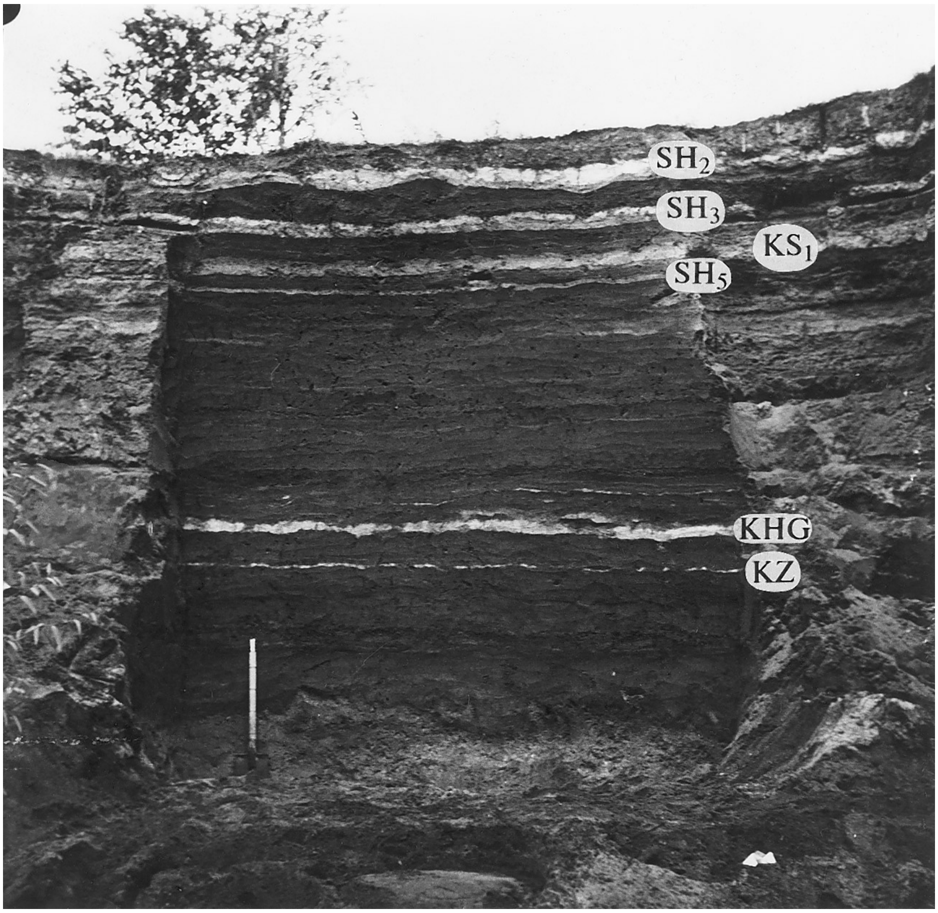

FIG. 1. A typical section of Holocene soil-pyroclastic cover overlying glacial deposits in Kliuchi town. Marker ash layers (for designations see Table 1) are separated by eolian sandy loams containing thin beds of ashes from nearby volcanoes, mainly Kliuchevskoi and Shiveluch. A schematic drawing of this section is shown in Figure 3, Section 2. The handle of a shovel in the left corner of the section is marked in 10-cm intervals.

STUDY METHODS

Direct field tracing of tephra layers. Our tephrochronological studies focused on the soil-pyroclastic cover, which was first studied near individual volcanoes in order to reconstruct their eruptive history (e.g., Braitseva *et al.*, 1983, 1991; Braitseva and Melekestsev, 1991; Melekestsev *et al.*, 1989; Ponomareva, 1990). We then made correlations along lengthy traverses in which detailed studies of soil-pyroclastic sections were made every 15 km (Braitseva *et al.*, 1989). The main traverse was along the Eastern Volcanic Belt of Kamchatka from Shiveluch volcano in the north to Kuril Lake in the south; many smaller cross profiles were also added (Fig. 2). Such features as color, stratification, and stratigraphic relationship with other layers make it possible to identify an individual ash layer in consecutive sections separated by only a few kilometers. As a result of these studies, ashes from most of the larger eruptions, which cover vast areas, were traced to their source volcanoes (Fig. 3).

Radiocarbon dating. Our technique for ^{14}C dating of volcanic deposits is summarized in Braitseva *et al.* (1993). We obtained more than 200 ^{14}C dates for soils, peat, wood, and charcoal from under and above each key-marker ash layer in the sections separated by tens to hundreds of kilometers (Fig. 3). In addition, we used the dates obtained for organic matter associated with the pyroclastic flows and surges of the same eruption. Most of these individual dates were published in Braitseva *et al.* (1987, 1988, 1995). For the average age calculations, we used the dates on charcoal, wood, and thin (1–3 cm) soil and peat layers which formed over a brief span of time. Dates from thick soil and peat layers, the formation of which might cover a long time interval, were used only in cases where dates were obtained for successive alkaline extractions, in which case we used the younger dates for the soil underlying and the older dates for the soil overlying the tephra. A date obtained for the thick soil or peat layer without subdivision into extractions gives its mean age and so may differ significantly from the age of under- or overlying tephra (Braitseva *et al.*, 1993). Stratigraphic relationships of tephra layers helped to reduce ^{14}C dating uncertainty. Only the dates used for averaging are shown in Figure 3; Table 1 shows weighted average ages

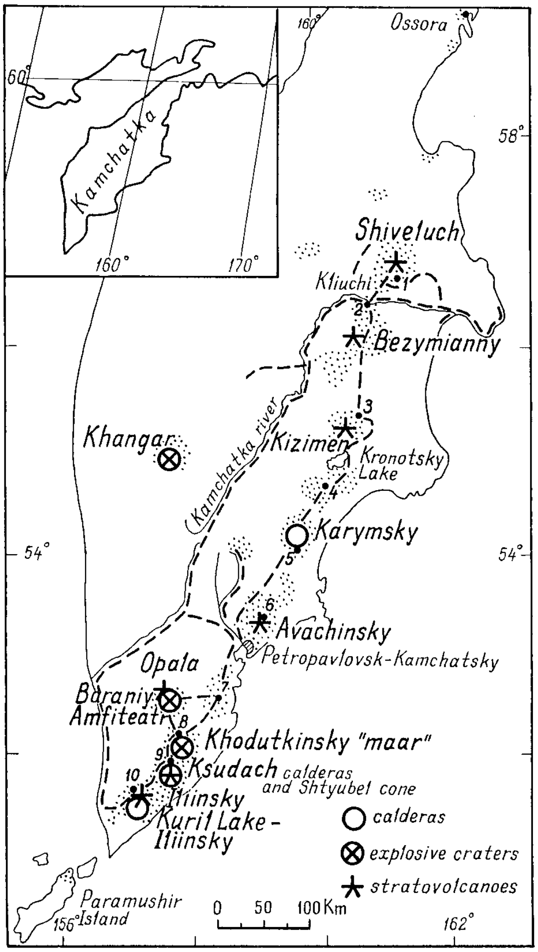

FIG. 2. Map of Kamchatka showing eruptive centers (sources of marker ash layers), tephrochronological traverses (dashed lines), and areas of detailed tephrochronological studies (small dots). Sections shown in Figure 3 are numbered.

of the key-marker tephra layers determined using the technique of Stuiver and Reimer (1993).

Mineralogy. The ashes of the largest Holocene explosive eruptions in Kamchatka contain a rather limited set of components. These are mainly volcanic glass, plagioclase, pyroxenes, and magnetite. In many ashes brown and green hornblende are present, and in a few ashes biotite occurs (Table 1). Apatite, olivine, quartz, zircon, and ilmenite occur as accessory minerals. Volcanic glass dominates in ashes, normally complemented by only small amounts of other minerals, and explains why it is difficult to correlate ash layers on the basis of the study of the bulk mineral composition (e.g., Kirianov *et al.,* 1990). More informative is the study of the mafic minerals (Geptner and Ponomareva, 1979), which allows us to identify biotite and hornblende as the most important mineral indicators in ashes. The absence or presence of these minerals makes it easier to distinguish between different ash layers (Table 1).

Geochemistry. At present, mostly major elements and a few trace elements have been measured on bulk samples of Kamchatkan ashes. No determinations on volcanic glass shards have been made. Still, it appeared possible to use the bulk major-element results for correlation of ash layers within the territory of Kamchatka. This correlation was then refined with the help of trace-element data.

The different ashes can be geochemically divided according to: (1) SiO_2, (2) K_2O and related incompatible elements (Rb, La), (3) Y, and (4) Mg, Cr, Ni, and Co. SiO_2 contents in marker ashes range from 50 to 75% (Fig. 4) and can vary significantly with distance from the vent (Ponomareva, 1988; Kirianov and Solovyova, 1991). The marker ashes represent magmas that ranged in composition from basaltic andesite to rhyolite. The only basaltic andesite marker ash is AV_1. Most ashes are andesitic to rhyodacitic, and only Opala and Baraniy Amfiteatr ashes are dominantly rhyolitic (Table 1).

According to Volynets (1994), Late Cenozoic volcanic rocks in Kamchatka can be subdivided into a few types based on K_2O index. The same is true for Holocene ashes, which differ in relative K_2O contents. Figure 4 is based on more than 400 bulk analyses, some previously published by Braitseva *et al.* (1989, 1991, 1996), Braitseva and Melekestsev (1991), Kirianov and Solovyova (1991), and Melekestsev *et al.* (1991, 1996a, 1996b). These data show that even if the bulk composition of any tephra-fall deposit changes significantly downwind, the ash belongs to the same geochemical type. This can be clearly observed in the example of the SH_{1964} and KO ash layers (Fig. 5). We sieved the samples taken near the vents and analyzed the resulting fractions (a), as well as the bulk samples taken along the direction of transport (b). It is clear that while the lapilli and fine ash of any fall deposit are similar and mostly silicic in composition due to the dominating volcanic glass, the coarse ash tends to be more mafic because of a relative enrichment in minerals. Nevertheless, all the SH_{1964} samples retain a medium K_2O index and KO retains a medium-to-low K_2O index (Fig. 4).

The La/Y_N–SiO_2 diagram (Fig. 6) shows a picture very similar to Figure 4 and allows us to distinguish better between ashes with low, medium, and high La/Y_N ratios. Y shows the opposite trend and is higher in low-K_2O series. Sr, Ni, Co, and especially Cr contents are very high in Shiveluch and Kizimen ashes (Table 2).

It is noteworthy that the trace-element analyses of KS_1, KO, and KRM ashes taken in the sections separated by hundreds of kilometers confirm our correlations in spite of the broad variations in SiO_2 content. If we compare the most mafic and the most silicic samples from KS_1 and KO ash layers, we can see that the most silicic samples generally have the usual geochemical features that go with higher SiO_2 in island-arc magmas (lower Ti, Al, Fe, Mn, Mg, Ca, P, Sr, Zn, Cu, Co, Ni, Sc, V, Cr, and Ga and higher K, Rb, Ba,

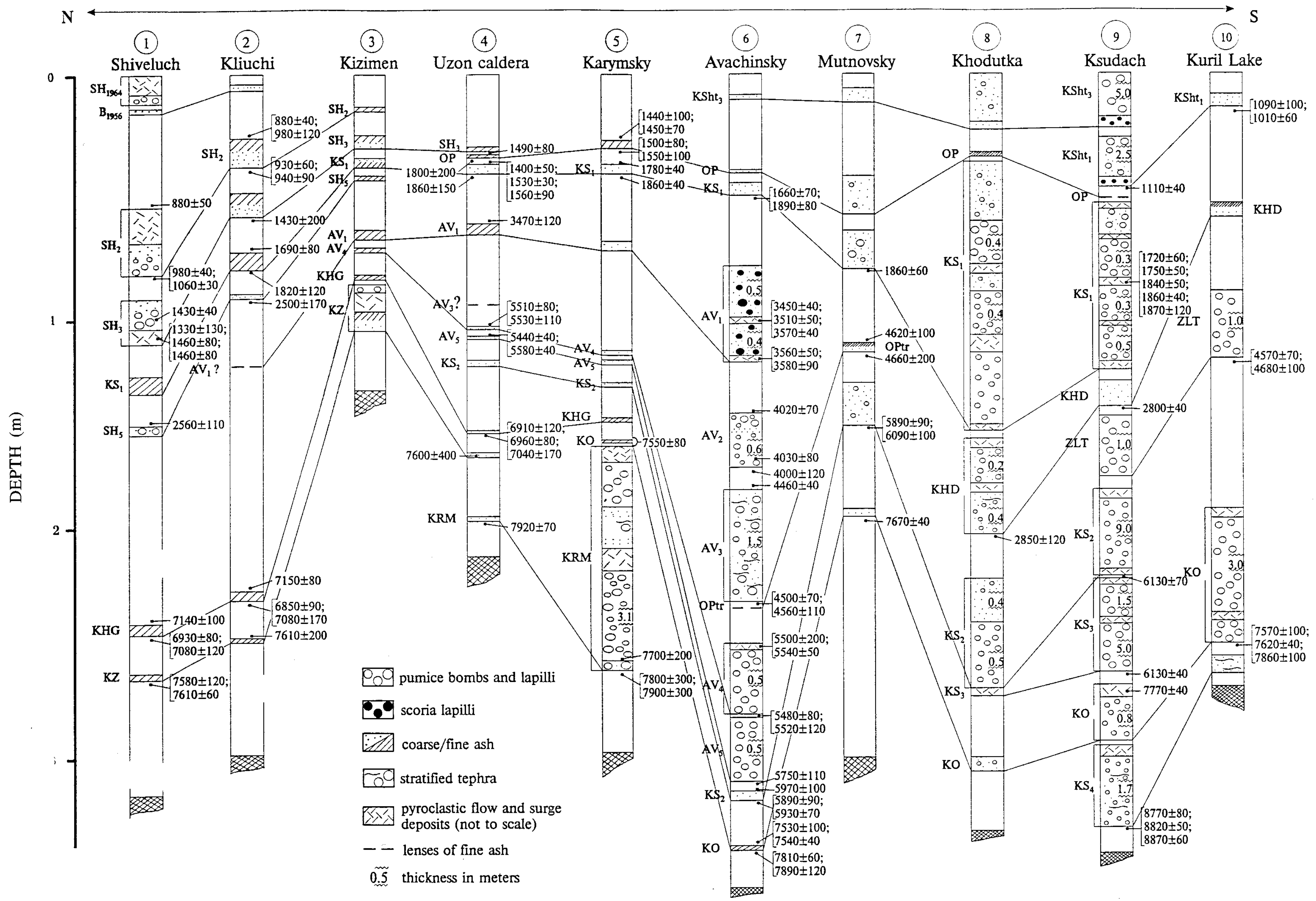

FIG. 3. Tephrochronological traverse along Kamchatka volcanic belt. The position of sections is shown in Figure 2. See Table 1 for ash-layer designations.

TABLE 1
Holocene Key-Marker Ash Layers in Kamchatka, Russia

Eruptive center	Code	Age (^{14}C yr B.P.)	Average composition of lapilli	General crystal assemblage	Characteristic features	Ash volume (km^3)
Caldera-forming eruptions						
Kuril Lake-Iliinsky	KO	7666 ± 19 (12)[a]	RD[b]	Pl + Px + Mt + Hb[c]	Low-medium K_2O content, presence of Hb	100–120
Karymsky caldera	KRM	7889 ± 67 (4)	RD	Pl + Px + Mt	Medium K_2O content, absence of Hb	8–10
Ksudach, caldera V	KS_1	1806 ± 16 (15)	RD	Pl + Px + Mt	Low K_2O content, absence of Hb	14–15
Ksudach, caldera IV	KS_2	6007 ± 38 (5)	A	Pl + Px + Mt	Low K_2O content, absence of Hb	7–8
Ksudach, caldera IV	KS_3	6130 ± 37 (2)	RD	Pl + Px + Mt	Low K_2O content, absence of Hb	0.5–1
Ksudach, caldera III	KS_4	8826 ± 40 (3)	A	Pl + Px + Mt	Low K_2O content, absence of Hb	1.3–1.4
Subcaldera eruptions						
Baraniy Amfiteatr	OP	1478 ± 18 (11)	R	Pl + Bi + Mt	High K_2O content, presence of Bi	9–10
Khodutkinsky Maar	KHD	2805 ± 40 (2)	RD	Pl + Px + Hb + Mt	Medium K_2O content, presence of Hb	1–1.5
Khangar	KHG	6957 ± 30 (10)	D	Pl + Hb + Px + Bi + Mt	Medium-high K_2O content, presence of Bi, Hb	12–13
Eruptions from stratovolcanoes						
Shiveluch	SH_{1964}	—	A	Pl + Hb + Px + Mt + Ol	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol	0.3
Shiveluch	SH_2	965 ± 16 (12)	A	Pl + Hb + Px + Mt + Ol	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol	⩾2
Shiveluch	SH_3	1404 ± 27 (8)	A	Pl + Hb + Px + Mt + Ol	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol	⩾1
Shiveluch	SH_5	2553 ± 46 (4)	A	Pl + Hb + Px + Mt + Ol	Medium K_2O content, high Cr and Sr content, presence of Hb, Ol	?
Avachinsky	AV_1	3512 ± 18 (10)	BA	Pl + Px + Mt + Hb	Low-medium K_2O content, presence of Hb	⩾2
Avachinsky	AV_2	4020 ± 49 (3)	A	Pl + Px + Mt + Hb	Low K_2O content, presence of Hb	⩾1
Avachinsky	AV_3	4481 ± 24 (7)	A	Pl + Px + Mt + Hb	Low K_2O content, presence of Hb	⩾1.5
Avachinsky	AV_4	5489 ± 27 (7)	A	Pl + Hb + Px + Mt	Low K_2O content, presence of Hb	⩾4
Avachinsky	AV_5	5602 ± 40 (2)	A	Pl + Px + Mt + Hb	Low K_2O content, small amount of Hb	⩾0.5
Benzymianny	B_{1956}	—	A	Pl + Px + Hb + Mt	Medium K_2O content, presence of Hb	0.4–0.5
Kizimen	KZ	7531 ± 37 (6)	D	Pl + Hb + Px + Mt	Medium K_2O content, presence of Hb	2.5–3
Opala	OPtr	4628 ± 90 (2)	R	Pl + Bi + Mt	High K_2O content, presence of Bi	?
Ksudach, Shtyubel cone	$KSht_3$	—	D	Pl + Px + Mt	Low K_2O content, absence of Hb	1.5–2
Ksudach, Shtyubel cone	$KSht_1$	1090 ± 31 (4)	D	Pl + Px + Mt	Low K_2O content, absence of Hb	0.8–1
Iliinsky (?)	ZLT	4606 ± 58 (2)	A	Pl + Px + Hb + Mt	Low-medium K_2O content, presence of Hb	1.2–1.4

[a] In column 3, figures in parentheses are the numbers of dates for average age calculations.
[b] A, BA, D, RD, R, are, respectively, andesite, basaltic andesite, dacite, rhyodacite, and rhyolite.
[c] Pl, plagioclase; Hb, hornblende; Px, pyroxene; Mt, magnetite; Ol, olivine; Bi, biotite. Minerals are given in order of diminishing contents.

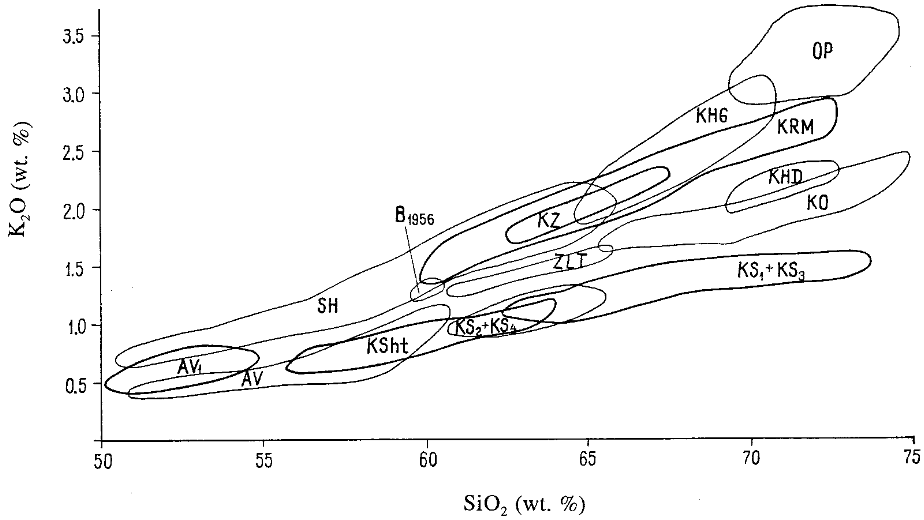

FIG. 4. Variation of K_2O content with SiO_2 content of ash marker deposits. SiO_2 and K_2O = wt.% on anhydrous basis. For ash-layer designations, see Table 1.

La, Ce, Nd, Y, Nb, and Cl). In general, the tephra transport trends are virtually identical with magmatic differentiation trends and suggest that a similar mechanism is operating, namely density separation of heavier crystals from a light groundmass.

ERUPTIONS

The explosive eruptions that produced marker ash layers were associated with (1) caldera collapse, (2) formation of large craters, and (3) stratovolcano activity. The eruptions of the first group resulted in the formation of five calderas: Karymsky, Kuril Lake-Iliinsky twinned caldera, and three calderas of the Ksudach volcanic massif (Fig. 7; Braitseva *et al.*, 1995). The eruptions of the second group resulted in the formation of three large craters: Baraniy Amfiteatr at the

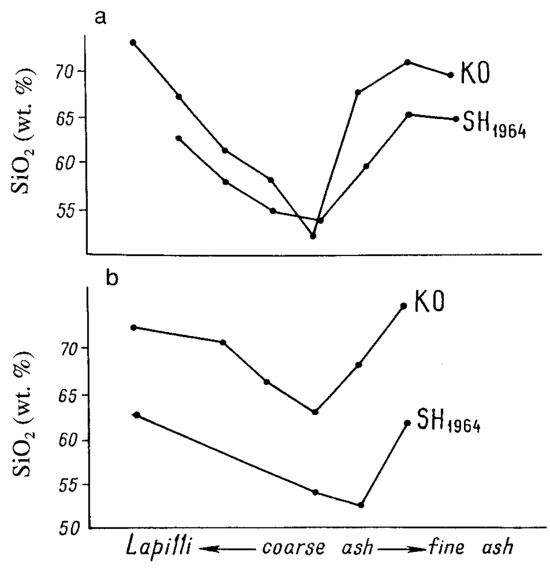

FIG. 5. Variations in SiO_2 content in KO and SH_{1964} ashes in fractions sieved from a single sample near the vent (a) and in the direction of transport of each layer (b). Dots show individual analyses.

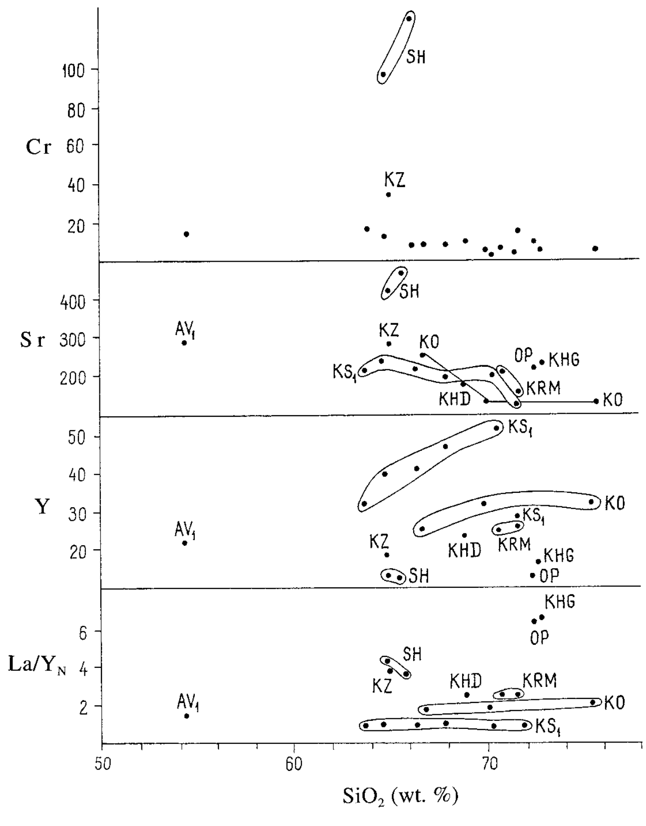

FIG. 6. Selected trace-element contents in marker ashes. SiO_2 = wt.% on anhydrous basis; Cr, Sr, and Y are in ppm. La/Y_N = chondrite normalized La/Y. For ash-layer designations, see Table 1.

TABLE 2
Partial Elemental Composition of Some Marker Ashes[a]

Ash layers:	KO			KRM		KS$_1$						OP	KHD	KHG	SH$_2$	SH$_3$	AV$_1$	KZ
Grain size[b]	c	f	f	l	f	l	l	c	c	c	f	c	f	f	f	f	f	f
SiO_2	66.7	70.7	75.3	70.5	71.6	67.8	70.0	64.1	66.5	64.6	72.4	72.6	69.4	72.5	64.5	65.4	55.1	64.9
K_2O	1.56	2.00	2.10	2.63	2.82	1.34	1.45	1.19	1.31	1.21	1.62	3.55	2.38	3.11	2.11	2.00	0.72	1.94
Rb	25	31	32	32	37	19	22	14	18	16	14	77	38	54	33	28	8.5	32
Ba	343	380	442	463	510	336	348	300	355	441	258	735	495	627	515	497	262	648
Sr	249	121	122	199	155	198	187	204	207	241	117	224	162	232	415	461	282	278
La	7	9	10	10	10	7	6	4	7	6	4	14	9	17	8	7	5	11
Ce	17	22	20	24	25	22	19	12	18	16	11	26	20	29	16	15	13	21
Nd	11	14	14	16	15	18	18	9	15	13	9	12	13	15	10	9	11	12
Y	26	32	32	25	26	47	52	31	41	39	28	14	24	17	13	12	22	18
La/Y_N	1.7	1.9	2.0	2.6	2.5	1.0	0.8	0.8	1.0	1.0	0.9	6.4	2.3	6.6	4.1	3.7	1.4	3.8
Nb	2.5	3.1	2.8	3.5	4.3	2.4	2.4	2.1	2.1	2.3	1.4	4.3	2.6	11	2.9	2.6	1.3	3.4
Zn	130	39	46	54	261	80	76	129	89	84	57	39	82	50	91	107	71	68
Cu	61	72	31	29	90	39	14	40	24	87	33	19	62	39	47	182	106	47
Co	6	3	<1	6	2	8	4	9	9	11	1	<1	4	<1	16	17	22	13
Ni	5	5	3	3	20	4	2	6	3	5	5	4	8	6	26	30	9	12
Sc	13	10	8	8	8	17	13	20	16	19	9	4	7	3	11	11	24	12
V	58	28	8	50	24	32	14	71	52	73	11	21	32	18	109	118	269	122
Cr	7	5	3	5	5	7	4	13	6	11	16	9	8	6	98	124	13	33
Ga	13	12	11	13	13	14	15	14	16	17	9	12	15	13	16	17	19	16

[a] Major elements were obtained by wet chemical techniques in the Institute of Volcanology. The traces were obtained by XRF analysis (Geology Institute, Copenhagen University) directly on powder pellets using a Phillips PW 1400 spectrometer. Matrix corrections were performed using major-element analyses and published absorption coefficients (Norrish and Chappell, 1977). Results were standardized against USGS reference materials and synthetic mixtures. SiO_2 and K_2O = wt.% on anhydrous basis; other elements are in ppm. La/Y_N = chondrite normalized La/Y.

[b] f, fine ash; c, coarse ash; l, pumice lapilli. Ash layer designations as in the text and Table 1.

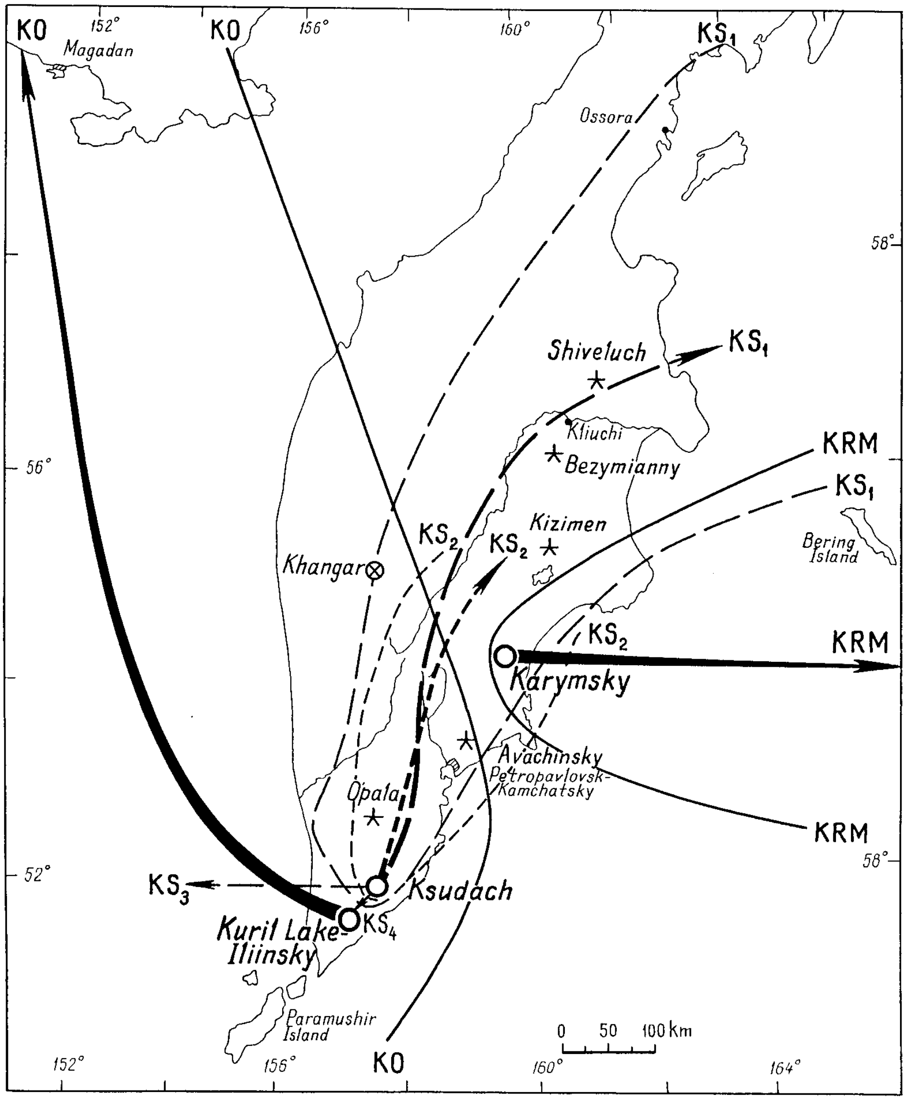

FIG. 7. Ash-fall axes and areas of ash dispersal (1-cm isopach) for caldera-forming eruptions. Symbols: see Figure 2.

foot of Opala volcano, Khodutkinsky Maar at the foot of Khodutka volcano, and the summit crater of Khangar (Fig. 8). These craters produced large volumes of pyroclastics comparable to those of the caldera-forming eruptions, but have no clear signs of collapse. Such eruptions are analogous to the Novarupta eruption of 1912 and were defined as a specific type of explosive event named a ''subcaldera eruption'' (Melekestsev *et al.,* 1996a). The most explosive eruptions of stratovolcanoes were those of Shiveluch and Avachinsky volcanoes (Table 1, Fig. 9). Only three historic eruptions were large enough to produce marker ash layers (SH_{1964}, B_{1956}, and $KSht_3$).

HOLOCENE KEY-MARKER TEPHRA BEDS

Tephra beds are listed in order of their source position from north to south. Radiocarbon ages and characteristic features of composition are given in Table 1.

Tephra of Shiveluch volcano. Shiveluch volcano is the northernmost of the active volcanoes of Kamchatka and one of the most active and prolific. During the last 8000 years at least 15 eruptions with tephra-fall volumes of about 0.5–1 km^3 each have occurred at Shiveluch. Here we describe only a few Shiveluch ash layers (SH_{1964}, SH_2, SH_3, and SH_5) which are better studied and are the important markers for the Kliuchevskoi volcanic group and other regions located to the south and east of Shiveluch (Braitseva *et al.,* 1983, 1988, 1989, 1991).

Proximal tephra-fall deposits of Shiveluch are mainly grayish or yellowish pumice lapilli. If a tephra fall had a distinct axis (e.g., SH_{1964} and SH_3), a transition from lapilli to coarse ash strongly enriched in minerals and then to fine glassy ash can be observed downwind (Kirianov and Solovyova, 1991). This explains significant changes in bulk chemical composition for an individual ash layer (e.g., SH_{1964}, one

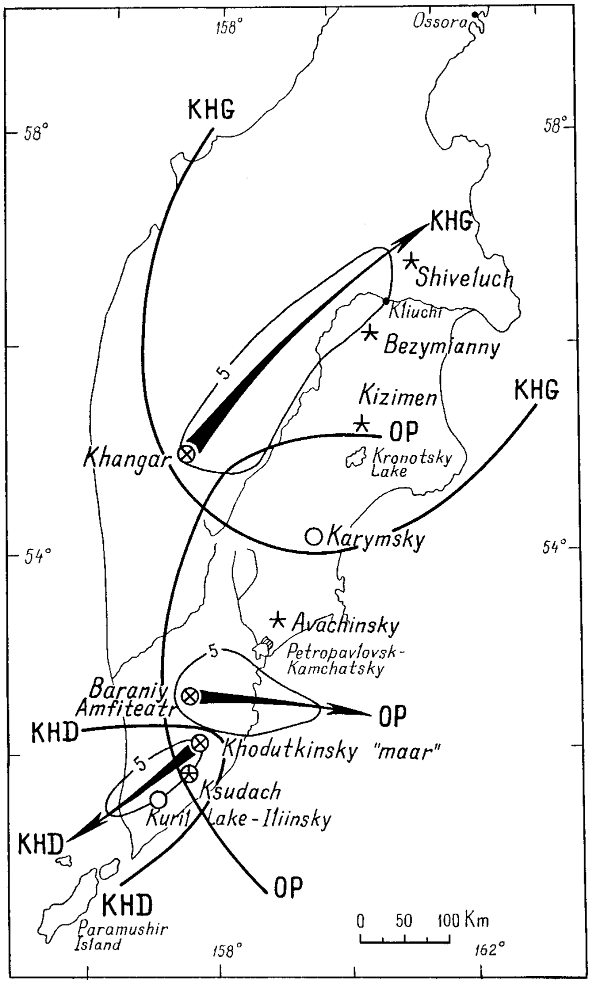

FIG. 8. Ash-fall axes, 5-cm isopachs, and areas of ash dispersal (1-cm isopach) for subcaldera eruptions. Other symbols: see Figure 2.

of the most pronounced among all the Kamchatkan ashes; Fig. 5) and likely results from the high content of mineral grains in the erupted magma. Bulk compositional changes are not so significant if a distal ash layer is composed of a mixture of coarse and fine ash, as is the case for the SH_2 and SH_5 ashes.

The general mineral assemblage of all the Shiveluch ashes includes plagioclase, green hornblende, magnetite, and pyroxene in various proportions; some ashes (SH_3, SH_5) contain brown hornblende. Olivine and apatite occur as accessory minerals. Lapilli and fine ash are medium-K_2O andesites; coarse ash is more mafic. Shiveluch ashes have the highest Mg, Sr, and especially Cr contents among other ashes in Kamchatka (Fig. 6), which helps to identify them easily.

SH_{1964} is associated with the well-known 1964 catastrophic eruption (Gorshkov and Dubik, 1969). The ashfall axis was directed to the SE (Fig. 9). The ash fall was witnessed as far as the Kommander Islands, but now the traces of this ash layer can be found there only rarely. Proximal tephra-fall deposits are light-gray andesitic pumice lapilli, in some sections underlain by a thin layer of gray fine ash. In Ust'-Kamchatsk, SH_{1964} ash almost entirely consists of mineral grains with only small amount of glass and is basaltic in bulk composition (Fig. 5), whereas on Bering Island it is andesitic fine ash (Kirianov and Solovyova, 1991). SH_2 is an ash from one of the most violent Plinian eruptions of Shiveluch volcano during the Holocene. It spread out in all directions from the volcano (Fig. 9). Proximal tephra fall deposits are normally graded, light-grayish andesitic pumice lapilli and more mafic coarse ash; at a distance of 45 km, the SH_2 layer consists of a lower coarse ash and an upper fine ash; at a distance of more than 135 km, it is dominantly white, andesitic fine ash (Fig. 3). The SH_3 ash-fall axis was directed to the south–southwest (Fig. 9) and the ash was traced in this direction for about 290 km. Proximal tephra is normally graded, yellowish pumiceous lapilli with an admixture of lithics. In Kliuchi, the SH_3 has the same stratigraphy as the SH_2 ash, with fine ash at the top and coarse ash at the bottom; at a distance of more than 135 km, SH_3 is dominantly fine ash. The SH_5 ash-fall axis was directed southwest. The ash was traced in the southern direction up

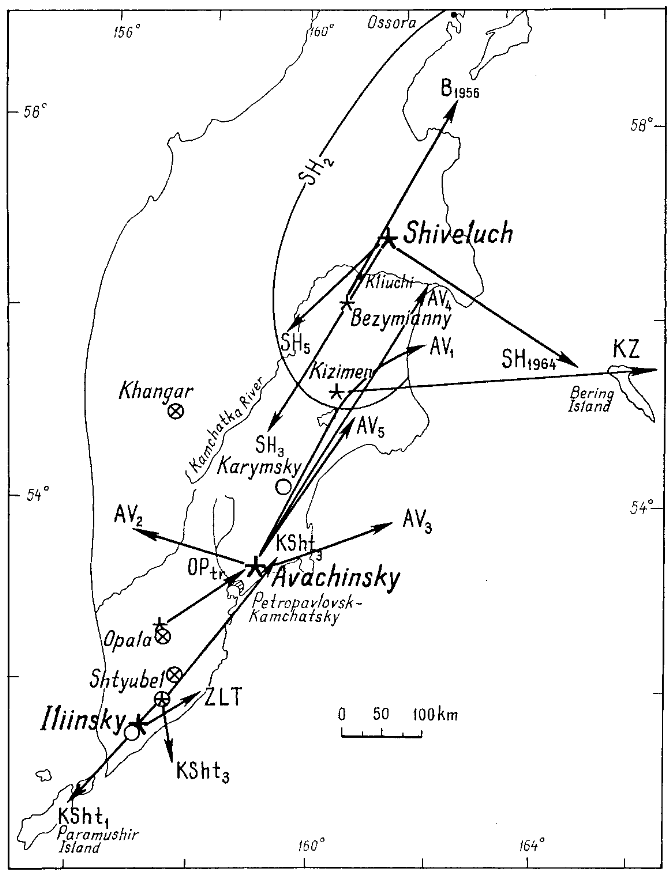

FIG. 9. Ash-fall axes for stratovolcano eruptions. For SH_2 ash, the area of dispersal is shown, as it has no distinct ash-fall axis. Other symbols: see Figure 2.

to Kizimen volcano (Fig. 3). Proximal ejecta are nonstratified yellowish pumice lapilli; in distal localities, the SH_5 is a yellowish fine ash.

Tephra of Bezymianny volcano. Tephra B_{1956} erupted during the well-known 1956 eruption (Gorshkov and Bogoyavlenskaya, 1965). The B_{1956} ash-fall axis was directed to northeast of the source (Fig. 9). In the distal localities, B_{1956} is a grayish coarse and fine ash and is a medium-K_2O andesite. It can be distinguished from SH_{1964} by finer grain size and lower Mg, Na, and Cr contents.

Tephra of Kizimen volcano. The KZ tephra is an important marker for the Kliuchevskoi volcanic group and Eastern volcanic zone (Figs. 1 and 3). Earlier, it was designated SH_7 and thought to be from Shiveluch volcano (Braitseva *et al.*, 1988, 1989). Proximal tephra-fall deposits are represented by a stratified packet of a lower coarse ash, intermediate yellowish fine ash, and upper yellowish pumice lapilli. Distal tephra is yellowish fine ash. Kirianov *et al.* (1990) identified KZ ash in a peat section on Bering Island, based on ^{14}C dates and a study of mineral composition. Lapilli and fine ash are medium-K_2O dacites; coarse ash is andesitic. Characteristic features helpful for distinguishing the KZ marker horizon from stratigraphically close KRM and KHG tephras are medium-K_2O content, abundance of hornblende, and lack of biotite.

Tephra of Karymsky caldera. The KRM tephra is dated about 7900 yr B.P., an age that correlates well with its stratigraphic position slightly below the KO ash which is dated 7700 yr B.P. (Fig. 3, Section 5). Pyroclastic deposits of this eruption are described in detail by Braitseva and Melekestsev (1991). Near the caldera they comprise two pumice bomb and lapilli units separated by ash-cloud surge deposits. Most of the tephra was dispersed to the east of the caldera (Fig. 7); ash thickness diminishes rapidly to the north and south. KRM ash is 3 cm thick on Bering Island, where it was earlier identified by Kirianov *et al.* (1990) based on ^{14}C dates and its mineral composition. Trace-element determinations confirm this correlation (Table 2, Fig. 6). The bulk composition of ash is dominantly medium-K_2O dacitic-rhyodacitic. This is a characteristic feature of KRM ash, as well as the absence of hornblende and biotite that helps to distinguish it from the stratigraphically close KZ and KHG ashes.

Tephra of Khangar volcano. KHG tephra is one of the best markers for the northern, central, and eastern parts of Kamchatka (Figs. 3 and 8). Earlier, while studying this tephra layer in the Kliuchevskoi volcanic group, we designated it SH_6 and thought it was from Shiveluch volcano (Braitseva *et al.*, 1983, 1988, 1989). The history of identification of the KHG layer (as well as a detailed account of ashes OP and KHD from other subcaldera eruptions) is presented by Melekestsev *et al.* (1996a). Near the vent it is represented by light-grayish, dominantly dacitic pumice bombs and lapilli, often covered with bright yellowish fine ash interstratified with coarse and fine ash horizons. The ash-fall axis is oriented to northeast (Fig. 8). At distances of more than 220 km, tephra KHG is a bright yellowish dacitic fine ash (Fig. 1). We traced it northward to the Ozernaya River (about 500 km away from the source; thickness about 2 cm) and eastward to Zhupanovsky volcano. The most prominent features of the KHG ash helpful for its identification are the presence of biotite and green hornblende, its dacitic composition, and its medium K_2O content.

Tephra of Avachinsky volcano. The Holocene activity of Avachinsky volcano may be roughly divided into two periods (Melekestsev *et al.*, 1989). During the earlier, it was dominated by voluminous Plinian eruptions which produced marker pumiceous ashes of andesitic composition (including AV_2, AV_3, AV_4, and AV_5 described in this paper). Beginning 3500 yr B.P., when a violent eruption produced marker ash layer AV_1, a stratocone composed mainly of basalts and basaltic andesites began to form (Braitseva *et al.*, 1995).

Proximal tephra-fall deposits of the marker ashes of the older period are mainly grayish or yellowish pumiceous bombs and lapilli. Distal tephras are dominantly yellow ashes. AV_1 tephra near the vent is represented by alternating layers of dark-grayish dense bombs, lapilli, and coarse ash of basaltic andesite composition (Fig. 3, Section 6). Distal tephra is coarse to fine gray ash. The general mineral assemblage of all Avachinsky ashes described here consists of plagioclase, hornblende, magnetite, and pyroxenes in various proportions. AV_1 ash composition everywhere corresponds to low-to-medium-K_2O, basalt to basaltic andesite, which makes it unique among other marker ash layers. AV_2, AV_3, and AV_4 are low-K_2O andesites. Significant changes in bulk chemical composition of AV_5 are observed downwind: lapilli are low-K_2O andesite but coarse ash is basaltic. A low K_2O index helps to distinguish Avachinsky ashes from stratigraphically close KHG and KZ layers, and the presence of hornblende from Ksudach ashes.

The AV_1 ash-fall axis was directed to the northeast. The ash was traced almost to the Kamchatka River (about 360 km away from the source; Figs. 3 and 9) and is a very important marker for eastern Kamchatka. Near the vent AV_2 is represented by two layers of pumice bombs and lapilli separated by coarse ash. Tephra was spread mainly to the west–northwest. AV_3 tephra near the vent is a stratified packet of pumice bombs and lapilli horizons alternating with coarse and fine ash layers. The ash-fall axis was directed to the east and most of the ash was spread over the ocean. Fine AV_3 ash could be found in the peat section on Bering Island. AV_4 and AV_5 tephra layers are separated by only a thin soil horizon. Both ashes were spread to the northeast (Fig. 9). Near the volcano they are represented by nonstratified pumice bombs and lapilli and at distances more than 40 km by yellowish coarse ash. Two closely spaced, bright yellowish layers are excellent markers for eastern Kamchatka and can be traced up to Kronotskoe Lake (190 km from the source). Farther afield, only the AV_4 layer composed of yellowish fine ash was traced to Kamchatka River (360 km from the source). AV_4 and AV_5 layers can be easily distinguished from one another: AV_4 has abundant hornblende which is rare in AV_5.

Tephra of Opala volcano. Tephra OP formed during one of the most voluminous Holocene eruptions of Kamchatka: that of Baraniy Amfiteatr crater, at the foot of Opala volcano (Melekestsev *et al.*, 1996a). Proximal deposits include a few alternating fall and flow units. Fall deposits are stratified white pumice bombs and lapilli with an admixture of coarse ash. The ash-fall axis was directed to the east (Fig. 8). Distal OP tephra is coarse to fine white ash. It was traced north to Kronotskoe Lake and south to Ksudach volcano (Fig. 3). Characteristic features of the OP ash are the predominance of volcanic glass (Kirianov and Solovyova, 1991) and the presence of biotite. The tephra is everywhere rhyolitic and has a high K_2O index (Fig. 4). These features help to distinguish tephra OP from the stratigraphically close SH_3 and KS_1 ash layers.

Tephra OP_{tr} was erupted by Opala volcano and is a good marker for the regions between Opala volcano and the Avachinsky volcanic group (Fig. 3). OP_{tr} ash is composed of yellowish, pumiceous, fine and coarse ash with an admixture of lapilli. The ash contains biotite and is a high-K_2O rhyolite that helps to distinguish it from Avachinsky ashes.

Tephra of Khodutkinsky Maar. KHD tephra is an important marker layer for the southernmost part of Kamchatka and Paramushir (Melekestsev *et al.*, 1996a). Proximal fall deposits are yellowish coarse ash with pumice lapilli and bombs. The ash-fall axis was directed to the southwest (Fig. 8). Near Zheltovsky volcano, it is white fine ash with lenses of coarse gray ash; further to the south it is fine white ash. In some of our earlier papers (e.g., Melekestsev *et al.*, 1990), tephra of Ksudach caldera V eruption (KS_1, see below) was mistakenly correlated with Khodutkinsky Maar because of its thickness and grain size, and it was designated KHD or KH. Later, the restudy of Khodutkinsky Maar and Ksudach tephrostratigraphy allowed us to identify KS_1 tephra and discriminate it from the KHD layer (Braitseva *et al.*, 1996). Bombs and lapilli, as well as the fine ash, of KHD are rhyodacitic; coarse ash is andesitic to dacitic. Characteristic features of KHD ash that help to distinguish it from Ksudach ashes are the presence of hornblende and the medium K_2O index.

Tephra of the Ksudach calderas and Shtyubel cone. Six ash marker horizons were produced by the Ksudach volcanic massif during the last 10,000 years. Four (KS_1, KS_2, KS_3, and KS_4) were associated with caldera-collapse events (Melekestsev *et al.*, 1996b), and two ($KSht_1$ and $KSht_3$) with eruptions of Shtyubel stratovolcano located in the most recent caldera. The most important markers are KS_1, KS_2, and both ashes of Shtyubel volcano. The mineral assemblage consists of plagioclase, pyroxenes, and ore minerals. Hornblende is lacking. The chemical composition ranges from basaltic andesites to rhyodacites but all the varieties are low-K_2O (Fig. 4). Characteristic features helpful for identification and correlation of KS marker horizons are their low K_2O content and lack of hornblende. These criteria combined with age determinations are sufficient to discriminate KS tephras from Shiveluch, Avachinsky, Opala, and Khodutka ashes that are close to some of the KS ashes stratigraphically and in SiO_2 abundance.

Tephra KS_1 is one of the most important regional marker horizons for Holocene stratigraphy because it covers almost all Kamchatka (Figs. 3 and 7). The detailed account of the KS_1 ash layer and the history of its identification in various parts of the peninsula are presented by Braitseva *et al.* (1996). In earlier publications it was designated SH_4 (Braitseva *et al.*, 1983, 1988, 1989, 1991) and KHD or KH (Melekestsev *et al.*, 1990). Proximal tephra-fall deposits are pumice lapilli and bombs. At least four bomb beds are identified, each underlying pyroclastic-flow deposits. Pumices of the lower three beds are white or yellowish and those of the upper bed are bluish-gray. The ash-fall axis was directed to the north. Within eastern Kamchatka, the KS_1 tephra is a yellowish, coarse to fine ash. In the Kamchatka River valley the tephra consists of two layers: yellowish coarse or fine ash below and gray fine ash at the top. These two layers correspond to two packets of pyroclastics at Ksudach volcano: a lower white or yellowish packet and an upper grayish one. Bombs and lapilli near the vent are rhyodacites. Both white and gray pumice bombs and lapilli at Ksudach and yellowish and gray fine ash at distal localities do not differ in composition and contain from 68 to nearly 72% SiO_2. Coarse ash is more mafic and contains 63–68% SiO_2. The most distal ash sample, in Ossora village at 900 km distance, has the highest SiO_2 content—72.4%. Notwithstanding the fact that the SiO_2 contents of ashes vary by 11%, all the samples fall into the field of low-K_2O rocks (Fig. 4).

The KS_2 and KS_3 tephras were produced by closely spaced eruptions resulting in the caldera IV formation (Melekestsev *et al.*, 1996b). Near the vent, KS_2 is represented by a thick packet of gray, dark-grayish, and purplish pumice bombs which are occasionally welded. KS_2 tephra was dispersed north of the vent and could be traced up to Kronotskoe Lake (370 km away from the source). Distal tephra is gray to dark-gray coarse ash, often iron-stained. The bulk composition of KS_2 ash is everywhere andesitic.

In some sections KS_3 tephra directly underlies KS_2, but in a few sections they are separated by a very thin sandy loam layer. At present, KS_3 ash has only been studied near the source, where it is represented mainly by snow-white pumice lapilli of rhyodacitic composition. The ash-fall axis was directed to the west (Fig. 7). KS_3 tephra must occur in the Sea of Okhotsk bottom sediments.

KS_4 tephra is represented near the source by stratified

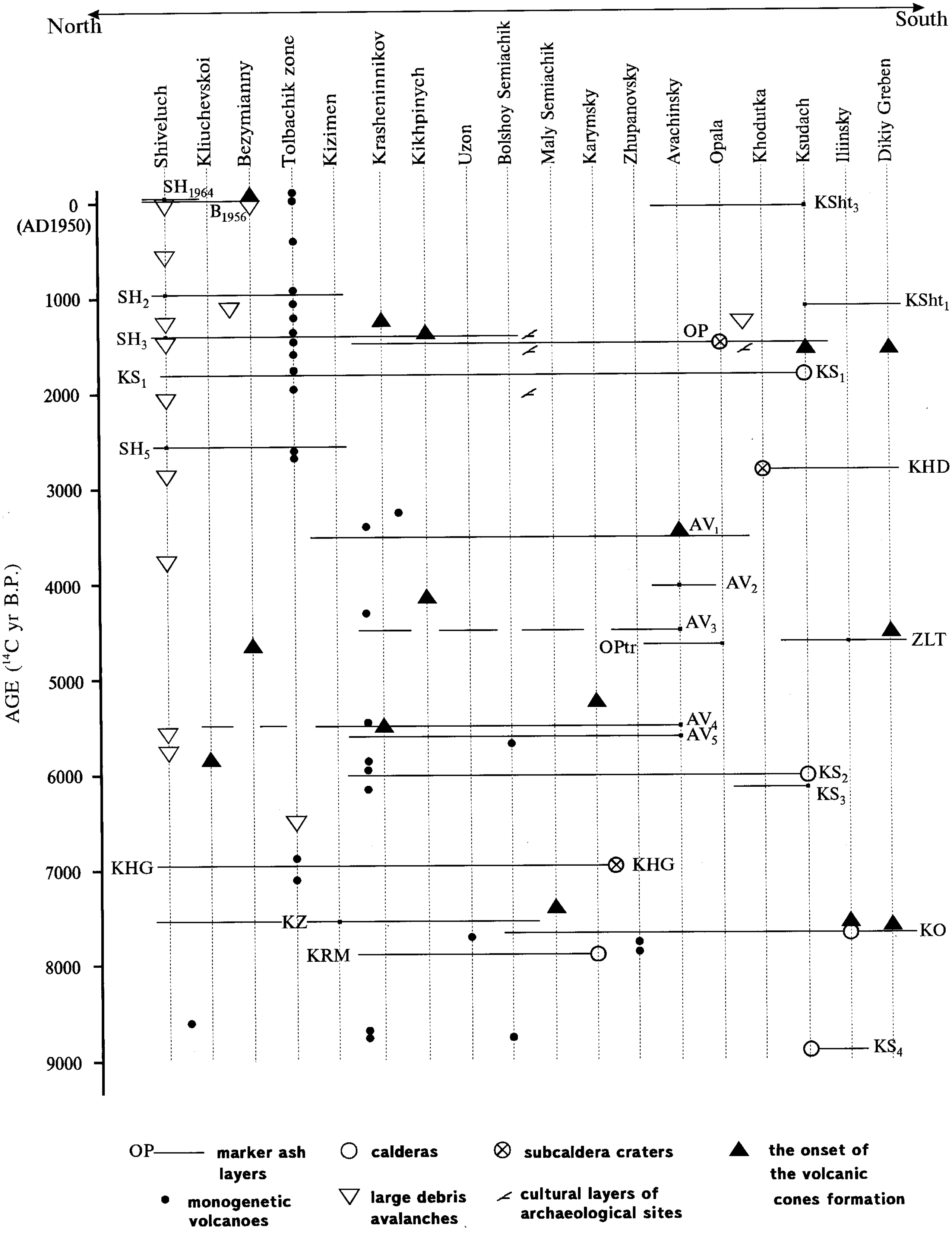

FIG. 10. Tephrostratigraphic framework for Holocene deposits in Kamchatka. Ages of various deposits and landforms and their position with respect to marker ash layers as in following papers: volcanic cones, Braitseva *et al.* (1995); debris avalanches at Shiveluch volcano, Ponomareva and Pevzner

black or light-brownish pumice bombs and lapilli; near the vent, they are occasionally welded. The ash-fall axis was directed to the southwest (Fig. 7). Distal tephra is stratified, gray coarse ash. Dark bombs are andesitic and light ones dacitic; the bulk composition of distal ash is dominantly andesitic.

$KSht_1$ ash layer was produced by Shtyubel cone. Near the vent it consists of two units. The lower unit is composed of black cinder bombs and lapilli of basaltic andesite (54–57% SiO_2), whereas the upper unit consists of white, pinkish, and yellowish dacitic pumice bombs (64–66% SiO_2). Both units are spread mainly to the southwest. At a distance of 30–45 km, $KSht_1$ tephra can easily be identified, as it retains its two-unit structure with a lower, thinner, dark-gray coarse ash layer and an upper, thicker, yellowish coarse ash layer.

$KSht_3$ is the ash of the 1907 historic eruption. Near the vent, $KSht_3$ stratification commonly resembles that of the $KSht_1$ layer: the lower unit is composed of black cinder bombs and lapilli (containing about 56% SiO_2) and the upper thicker unit is represented by gray, pinkish, and yellowish pumice bombs (61–68% SiO_2) with an admixture of black mafic bombs. Macias and Sheridan (1995) describe the still-more complicated stratification of fall deposits with few alternating black and light layers. The ash-fall was spread mainly northeast of the volcano and can be traced in this direction for 200 km up to Avachinsky volcano. At distances more than 60 km, the tephra is coarse andesitic ash.

Tephra of the Kuril Lake-Iliinsky caldera. Tephra fall layer KO is a very important Early Holocene marker for the southern part of Kamchatka. It was associated with the largest Holocene explosive eruption in Kamchatka. Total pyroclastic volume is estimated to be 120–140 km^3 and tephra-fall volume 100–120 km^3 (Table 1). Near the vent, the KO ejecta include white airfall bombs and lapilli and pyroclastic flow and surge deposits (Fig. 3). Ash KO was dispersed in a broad sector mainly to the west and northwest of the source (Fig. 7). It is 5 cm thick as far as the Magadan region more than 1000 km away (Melekestsev *et al.*, 1991) and was also identified by Melekestsev on Paramushir and Onekotan (Kuril Islands). The KO layer has been traced to the north, up to Karymsky volcano, where it overlies deposits of Karymsky caldera (Fig. 3). At a distance of 60 km northeast of the vent, the tephra is a mixture of yellowish, fine to coarse ash; at more distal localities, it is a fine pale-yellowish ash. The general mineral assemblage of the KO ash comprises plagioclase, pyroxenes, magnetite, and hornblende. The ejecta are dominantly medium-K_2O rhyodacites. The composition of tephra-fall deposits ranges from rhyodacitic (bombs, lapilli, and fine ash) to dacitic (coarse ash). The field of KO analyses has an intermediate position between KS and KRM ashes (Fig. 4). Characteristic features helpful for identification and correlation of KO marker horizon are: (1) SiO_2 contents 63–74%, (2) medium K_2O content intermediate between the KS and KRM ashes, and (3) minor amount of hornblende. These criteria combined with data on ages and stratigraphy are sufficient to discriminate tephra KO from KRM and KS_{2-4} which are close to tephra KO stratigraphically and in SiO_2 abundance.

Tephra of Iliinsky volcano (?). In the regions between the Ksudach massif and the Ozernaya River, a remarkable bed of yellowish pumice bombs and lapilli was described as a marker horizon with an age of about 5000 yr B.P. It was attributed to Zheltovsky volcano and designated ZLT based on its thickness and grain size in the sections then measured (Braitseva *et al.*, 1992; Melekestsev *et al.*, 1996b). Our recent detailed studies in this area suggest that this bed is more likely associated with an Iliinsky volcano eruption; its age is refined to about 4600 yr B.P. (Ponomareva *et al.*, 1995). Nevertheless, we decided to retain the earlier designation of ZLT for this bed until unambiguous identification of its source is possible. The ash-fall axis was directed to the northeast. The dominant composition of bombs and lapilli is andesitic, although more-mafic black varieties also occur. ZLT pumice contains hornblende, which allows us to distinguish it from Ksudach pyroclastic deposits. In Figure 4, the ZLT points have the same intermediate position between low-K_2O and medium-K_2O ashes as the KO ash. The ZLT pumice bed is a very important marker for the complicated Holocene tephrostratigraphy of the Kuril Lake region.

KEY MARKER ASH LAYERS AS THE BASIS OF THE TIMESCALE FOR HOLOCENE STRATIGRAPHY IN KAMCHATKA

The marker ash horizons form a detailed timescale over most of Kamchatka and offer the possibility of dating various Holocene deposits and correlating distant sections (Fig. 10). This timescale can be observed in nature in the peat sections because even the thinnest ash layers are clearly seen. Key marker horizons have been used for dating both volcanic and nonvolcanic landforms and deposits.

Dating of volcanic landforms and deposits by measuring

(1995); archaeological sites, Braitseva *et al.* (1987) and Melekestsev *et al.* (1990). Horizontal side of the triangles marks the time of the events. Debris avalanche from Kamen volcano (Braitseva *et al.*, 1991) is shown between Kliuchevskoi and Bezymianny volcanoes and the one from Mutnovsky volcano (Melekestsev *et al.*, 1990) between Opala and Khodutka volcanoes. Lavovy Shysh lava field (Braitseva *et al.*, 1995) is shown between Shiveluch and Kliuchevskoi volcanoes and cinder cones of the Krasheninnikov volcano region immediately to the north and south of the latter.

overlying tephra sections and identifying the lowermost marker ash horizon in them, along with radiocarbon dating, allowed us to determine the age of calderas, large craters, and most of the active volcanoes in Kamchatka (Braitseva *et al.*, 1995) and to reconstruct their eruptive histories (e.g., Braitseva *et al.*, 1983, 1991; Braitseva *et al.*, 1991; Melekestsev *et al.*, 1990, 1996b; Ponomareva, 1990). In addition, marker ash layers were used for dating river and marine terraces, landslides, lahar and tsunami deposits, faults (e.g., Melekestsev *et al.*, 1990, 1994), Holocene glacial events (Solomina *et al.*, 1995), and archaeological sites (Braitseva *et al.*, 1987). It also is possible to use these ash layers to correlate various facies of distant deposits, to date and reconstruct paleo-landforms, to determine the depositional rate of lacustrine, marine, eolian sediments, and peat, and to calculate erosion rates. The studied marker tephra layers provide a record of the most voluminous explosive eruptions in Kamchatka during the Holocene and thus indicate some major endogenic events and register volcanic input into the atmosphere.

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