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Ages of calderas, large explosive craters and active volcanoes in the Kuril–Kamchatka region, Russia

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Abstract The ages of most of calderas, large explosive craters and active volcanoes in the Kuril–Kamchatka region have been determined by extensive geological, geomorphological, tephrochronological and isotopic geochronological studies, including more than 600 ^{14}C dates. Eight 'Krakatoa-type' and three 'Hawaiian-type' calderas and no less than three large explosive craters formed here during the Holocene. Most of the Late Pleistocene Krakatoa-type calderas were established around 30000–40000 years ago. The active volcanoes are geologically very young, with maximum ages of about 40000–50000 years. The overwhelming majority of recently active volcanic cones originated at the very end of the Late Pleistocene or in the Holocene. These studies show that all Holocene stratovolcanoes in Kamchatka were emplaced in the Holocene only in the Eastern volcanic belt. Periods of synchronous, intensified Holocene volcanic activity occurred within the time intervals of 7500–7800 and 1300–1800 ^{14}C years BP.

Key words Caldera ages · Explosive crater ages · Active volcanoes · Kuril–Kamchatka · Russia

Introduction

More than 60 volcanoes within the Kuril–Kamchatka island arc have been recently active (Vlodavets 1957). In Kamchatka, most active volcanoes occur in the Eastern volcanic belt, which extends southward from Shiveluch volcano (56°47′N) in the north along east and south Kamchatka to the southern termination of the peninsula (51°N). A few volcanoes are located to the west of the belt (Fig. 1).

For more than 20 years our investigations within the Kuril–Kamchatka region have focused on documenting and dating the most significant volcanic events that occurred during the last 30000–40000 years. The first studies were in the 1960s and 1970s, when complex geological-geomorphological techniques of dating volcanoes were developed (Melekestsev et al. 1970). Ages were determined from the following data: (1) specific morphological features and the degree of edifice preservation, which, among other things, is a function of time; (2) concordance with the topography and deposits, the age of which are known (mainly from the glacial formations of different ages); (3) lenses and bands of terrigenous deposits in volcanic rocks dated by spore pollen and diatomic methods; and (4) the position of intercalated tephra in the dated continental deposits and sea bottom sediments of adjacent marine areas. These techniques allowed the recognition of several groups of extinct and active volcanoes of different ages in Kamchatka (Table 1; Melekestsev et al. 1971). Most of the active volcanoes in the Kuril–Kamchatka region are geologically very young, having formed in the Late Pleistocene–Holocene (Melekestsev 1973). By 'active volcano' here, we mean its recently active cone, but not the whole volcanic center, the formation of which could have covered a much longer period of time. Volcanoes of groups I and II in Table 1 are inactive.

Essential progress in the study of the ages of volcanic landforms in Kamchatka has been made during the last 20 years due to detailed tephrochronological investigations and much radiocarbon dating. This paper presents a detailed account of the ages of most calderas, large explosive craters and recently active volcanoes in the Kuril–Kamchatka region based on geological, geomorphological and tephrochronological studies, and more than 600 ^{14}C dates.

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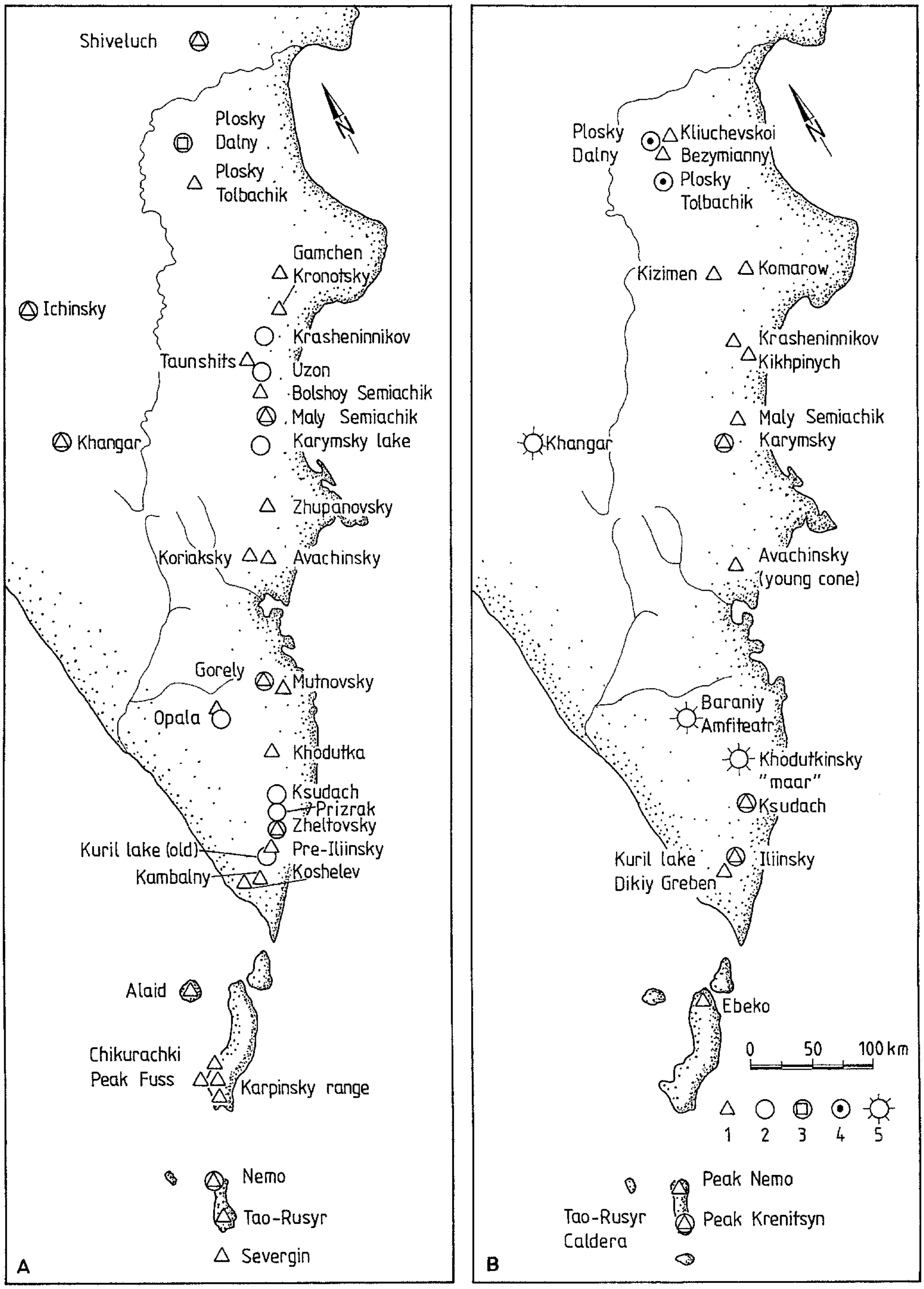

Fig. 1 **A** Map showing active and potentially active volcanoes which originated in the Late Pleistocene and Late Pleistocene calderas. **B** Map showing active volcanoes, calderas and craters of subcaldera eruptions which formed in the Holocene or at the very end of Late Pleistocene. **1,** Multi-eruptive volcanoes (dominantly stratovolcanoes); **2,** Krakatoa-type calderas; **3–4,** Hawaiian-type calderas; and **5,** craters of subcaldera eruptions. Volcanoes, calderas and craters are not to scale

Study methods

Dating of Holocene volcanic landforms

Tephrochronology

The tephrochronological studies focus on the soil–pyroclastic sequence, which consists of tephras from different volcanoes separated by soils, eolian sandy loams or peats, and represents a geological chronicle of the explosive volcanic eruptions. The Holocene soil–pyroclastic sequence is a few tens of centimeters thick in the areas distant from the active volcanoes and increases up to several meters at their foot (Fig. 2). Firstly, we studied the soil–pyroclastic sequence near individual volcanoes to reconstruct their eruptive history. We then made correlations along long traverses in which detailed studies of soil–pyroclastic sections were made every 15 km. 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. As a result of these studies, ashes from most of the larger eruptions, which cover vast areas, were traced to their volcano source. The correlations were checked and added to by studies of the bulk composition of ashes and by ^{14}C dating.

Table 1 Age groups of Quaternary stratovolcanoes of Kamchatka

When the volvanoes formed	Volcanic edifice preservation	Correlation with glacial forms	Example volcanoes
IV Holocene	Well preserved edifices and no traces of erosion are present	No traces of Late Pleistocene glaciation. Recent glaciers occur occasionally	Kliuchevskoi, Bezymianny, Krasheninnikov, Karymsky, Maly Semiachik
III Second half of Late Pleistocene with continuing Holocene activity	Initial view of volcanic edifice is preserved. Cones begin to be dissected by deep gullies	No sculptural glacial forms. Large fields of moraine deposits are located at the feet of volcanoes	Ostry Tolbachik, Opala, Kronotsky, Taunshits, Khodutkinsky
II Late Pleistocene before the onset of stage II of Late Pleistocene glaciation	Some eroson of volcanic edifices. Large areas of the original slopes are preserved	Small and scarce sculptural forms (cirques, troughs) of stage II of Late Pleistocene glaciation are present. Moraines are located at the feet of volcanoes	Volcanoes of the Bolshoy Semiachik group, Vershinsky, Anaun
I Mid- and early Late Pleistocene	Strongly and moderately destroyed edifices with fragments of the original slopes	Well expressed sculptural glacial forms. Moraines of two stages of Late Pleistocene glaciation are located at the feet of volcanoes	Gorny Zub, Unana, Zhupanovskie Vostriaki, Aag, Arik

These tephrochronological studies resulted in a stratigraphic scale of tephra marker beds for the Holocene in Kamchatka (Table 2; Braitseva et al. 1992b; 1993). We have determined the areas of distribution for all marker ashes, as well as their characteristic features needed for correlation, including the stratigraphic positions of ashes, regularities in changes of particle diameter and thickness with increasing distance from the source, ages and bulk composition. The distinctive features of bulk composition of any ash are as follows: the presence or absence of mineral indicators such as biotite and hornblende and K_2O concentration. These data allow the identification of marker ashes in soil–pyroclastic sequences in any region of Kamchatka. The ash horizons may be used as time markers for the determination of the age of deposits and landforms.

Radiocarbon dating

Our technique for ^{14}C dating of Kuril–Kamchatka volcanic deposits is summarized in Braitseva et al. (1992a; 1993). Along with traditional dating on charcoal and wood, we also used buried soils and peat for dating. In soil–pyroclastic deposits these soils are commonly represented by thin ((1–5 cm) humic horizons. This organic matter is good for dating as it is well preserved by the pyroclastic deposits and typically represents only a short span of time. Provided a sufficient amount of organic material is available, it is possible to date several successive alkaline extractions from the same soil or peat sample. We believe that the results of the first and last extractions are close to the termination and onset of soil or peat layer formation. A date obtained without subdivision into extractions shows the mean age of the buried soil (for example, see section 6 in Fig. 3A). It is evident that the youngest dates of alkaline extracts are close in age to the overlying pyroclastic deposits.

Care must be taken with the soils or peat that overlie the pyroclastic deposits because the formation of the latter may sometimes be delayed depending on the growth rates of vegetation on fresh pyroclastic material. Nevertheless, the oldest dates of alkaline extracts from the soil overlying fine ash often show good concordance with the youngest dates from the soil underlying the same pyroclastic deposits (Fig. 3) and can be also used for timing the eruption.

The dates derived from charcoal and wood from the pyroclastic deposits are usually in good concordance with those obtained on peat and buried soils at the same stratigraphic level (Braitseva et al. 1992a; 1993). Some difficulties arise only in dating charcoals in pyroclastic flow and surge deposits as such charcoals and sometimes prove to be older the underlying soils (Figs 3C and 4; Sulerzhitsky 1970; Rubin et al. 1987; Braitseva et al. 1992a; 1993).

Tephrostratigraphic correlation of tephra marker beds allows results to be checked by comparing dates for the same stratigraphic intervals in soil–pyroclastic sections separated by tens to hundreds of kilometers (Fig. 3).

Dating of Late Pleistocene volcanoes and calderas

The above-described technique, unfortunately, cannot be used for volcanoes that formed earlier than the Holocene, as the pre-Holocene soil–pyroclastic layers in the Kuril–Kamchatka region were almost everywhere destroyed by denudation processes during the great Late Pleistocene glaciation. In addition, deposits of this age, accumulated under cold conditions during the glaciation, are extremely poor in organic matter. However,

Fig. 2 Soil–pyroclastic sequence at the foot of Maly Semiachik volcano (generalized section is presented in Fig. 4). Pyroclastic deposits associated with the formation of Karymsky caldera (KRM) are seen below, pyroclastics (KS) of Maly Semiachik volcano (Kaino-Semiachik) lie above. KRM eruption and pyroclastics of early Kaino-Semiachik eruptions are dated on buried soils (S) underlying them. Above are cinders associated with the large Kaino-Semiachik eruption, which occurred about 4000 years ago

the radiocarbon method in some instances dates pyroclastic deposits from caldera-forming eruptions associated with charcoal and buried soils.

K–Ar dating for young Pleistocene volcanic rocks was not used because of low K concentrations in Kuril–Kamchatkan rocks. The fission track method is also infrequently used because the deposits are poor in apatite and zircon; only single dates obtained on volcanic glass are available (Masurenkov 1980a).

For age identification of Late Pleistocene volcanoes we use the glacial deposits of the Late Pleistocene glaciation: moraines of stage I (analogous to the Early Wisconsinian of North America) and stage II (analogous to the Late Wisconsinian). In the deposits of the Late Interglacial (Interglacial Sangamon in North America), the spore–pollen spectra indicate a warmer climate than the contemporary climate and are a good age marker in Kamchatka (Braitseva et al. 1968). Data on the absolute age of glacial and interglacial deposits in the Kuril–Kamchatka region are meager and we arbitrarily assign ages based on stratigraphic analogues in North America: stage I, 79000–65000 years; stage II, 35000–10000 years;and Late Pleistocene Interglacial, 132000–79000 years (Sibrava et al. 1986).

Holocene volcanic landforms

Holocene calderas

The ^{14}C ages of all Holocene calderas in Kamchatka and the Kuril Islands have been determined (Table 3, Figs 1B and 5A).

Karymsky caldera (Fig. 6), within which Karymsky volcano is located, formed about 7700–7800 years ago (Braitseva and Melekestsev 1991). The age of charcoal from the pumice lapilli layer at the base of the caldera pyroclastic deposits is 7700±200 years (Table 3, Fig. 4). Ages of 7800–7900 years have been determined for the uppermost soil layer buried by these pyroclastic deposits. The date 7550±80 years was derived from the thick soil overlying the caldera pyroclastic units and is likely to be substancially younger as it determines the mean age of the whole soil horizon (see under Study methods). Charcoals from pyroclastic flow and surge deposits are systematically older, ranging from 8000 to 8600 years (Table 3, Fig. 3). Because of the large scattering of data, we regard the dates of more than 8000 years to be too old and give preference to the concordant dates obtained on charcoals from the lapilli layer and from the underlying and overlying soils.

The Kuril Lake caldera was initially considered to be of Holocene age, because its pyroclastic deposits overlie glacial deposits of phase II of the Late Pleistocene glaciation. The radiocarbon age of the Kuril Lake caldera was previously thought to be about 8000 years (Kraevaya 1967; Masurenkov 1980b) as most age determinations on charcoal and buried soils ranged from 8000 to 8400 years. This age, however, disregarded two dates then available (obtained by L. D. Sulerzhitsky); one on underlying peat (7860±100) and one on wood from this peat (7620±50).

Our new dates show that the ages of underlying soils range from 7570 to 8150 years (Table 3, Fig. 3C). However, the youngest dates are 7570–7860 years. A new charcoal age from pyroclastic flow deposits was determined to be 7770±40 years. Previously reported dates of 8340–8400 years obtained on charcoal from the basement of the caldera pyroclastic deposits (Masurenkov 1980b) seem to be too old (Braitseva et al. 1993). The oldest dates on soils overlying the pyroclastic deposits range from 7530 to 7670 years BP, and are in good agreement with the youngest dates obtained on the soils underlying them.

Table 2 Key marker tephras of the largest prehistoric Holocene volcanic eruptions in Kamchatka

Source	Tephra layer	^{14}C age (years)	Composition*	General crystal assemblage⁺	Characteristic features	Tephra volume (km^3)‡
Caldera-forming eruptions						
Karymsky caldera	KRM	7700–7800	RD	Pl + OPx + CPx + Mt + Ilm	Medium K_2O content, absence of Hb	8–10
Kuril Lake caldera	KO	7600–7700	R	Pl + OPx + CPx + Mt + Hb	Medium K_2O content, presence of Hb	100–120
Ksudach calderas						
Caldera V	KS_1	1700–1800	RD	Pl + OPx + CPx + Mt	Low K_2O content, absence of Hb	15
Caldera IV	KS_2	~6000	A	Pl + OPx + CPx + Mt	Low K_2O content, absence of Hb	8–9
	KS_3	~6100	RD + A	Pl + OPx + CPx + Mt	Low K_2O content, absence of Hb	?
Caldera III	KS_4	8700–8800	A	Pl + OPx + CPx + Mt	Low K_2O content, absence of Hb	1.5
Subcaldera eruptions						
Opala (Baraniy Amfiteatr)	OP	1400–1500	R	Pl + Bi + Mt	High K_2O content, presence of Bi	9–10
Khodutkinsky maar	KHD	~2800	RD	Pl + OPx + Hb + Mt	Medium K_2O content, presence of Hb	> 1
Khangar	KHG	6900–7000	D	Pl + Hb + OPx + CPx + Bi + Mt	Medium K_2O content, presence of Hb, Bi	>10
Stratovolcano eruptions						
Shiveluch	SH_2	~ 900	A	Pl + Hb + OPx + CPx + Mt + Ol	Medium K_2O content, presence of Hb, Ol	> 2
	SH_3	1300–1400	A	Pl + Hb + OPx + CPx + Mt + Ol	Medium K_2O content, presence of Hb, Ol	2
	SH_5	2500–2600	A	Pl + Hb + OPx + CPx + Mt + Ol	Medium K_2O content, presence of Hb, Ol	> 1
Avachinsky	AV_1	~3500	BA	Pl + OPx + CPx + Mt + Hb	Low K_2O content, presence of Hb	> 4
	AV_2	4000–4100	A	Pl + OPx + CPx + Mt	Low K_2O content	> 0.5
	AV_3	4500–4600	A	Pl + OPx + CPx + Mt + Hb	Low K_2O content, presence of Hb	> 0.5
	AV_4	5400–5500	A	Pl + Hb + OPx + CPx + Mt	Low K_2O content, presence of Hb	> 1
	AV_5	~5600	A	Pl + OPx + CPx + Mt	Low K_2O content	> 0.5
Bezymianny	BZ	~2300	A	Pl + OPx + CPx + Hb + Mt	Medium K_2O content, presence of Hb	0.3–0.4
Kizimen	KZ	7500–7600	D	Pl + Hb + OPx + CPx + Mt + Ilm + Ol	Medium K_2O content, presence of Hb, Ol	2.5–3.0
Zheltovsky	ZLT	~5000	A	Pl + OPx + CPx + Hb + Mt	Low–medium K_2O content presence of Hb	1.2–1.4
Ksudach, Shtyubel volcano	KS-SHT	1000–1100	D	Pl + OPx + CPx + Mt	Low K_2O content, absence of Hb	0.8

* A, BA, D, RD, R: andesite, basaltic andesite, dacite, rhyodacite, rhyolite, respectively.
⁺ Minerals are given in order of diminishing contents. K_2O classification according to Gill (1981).
‡ Volumes of Ksudach tephras are refined after (Braitseva et al. 1992b) was published.

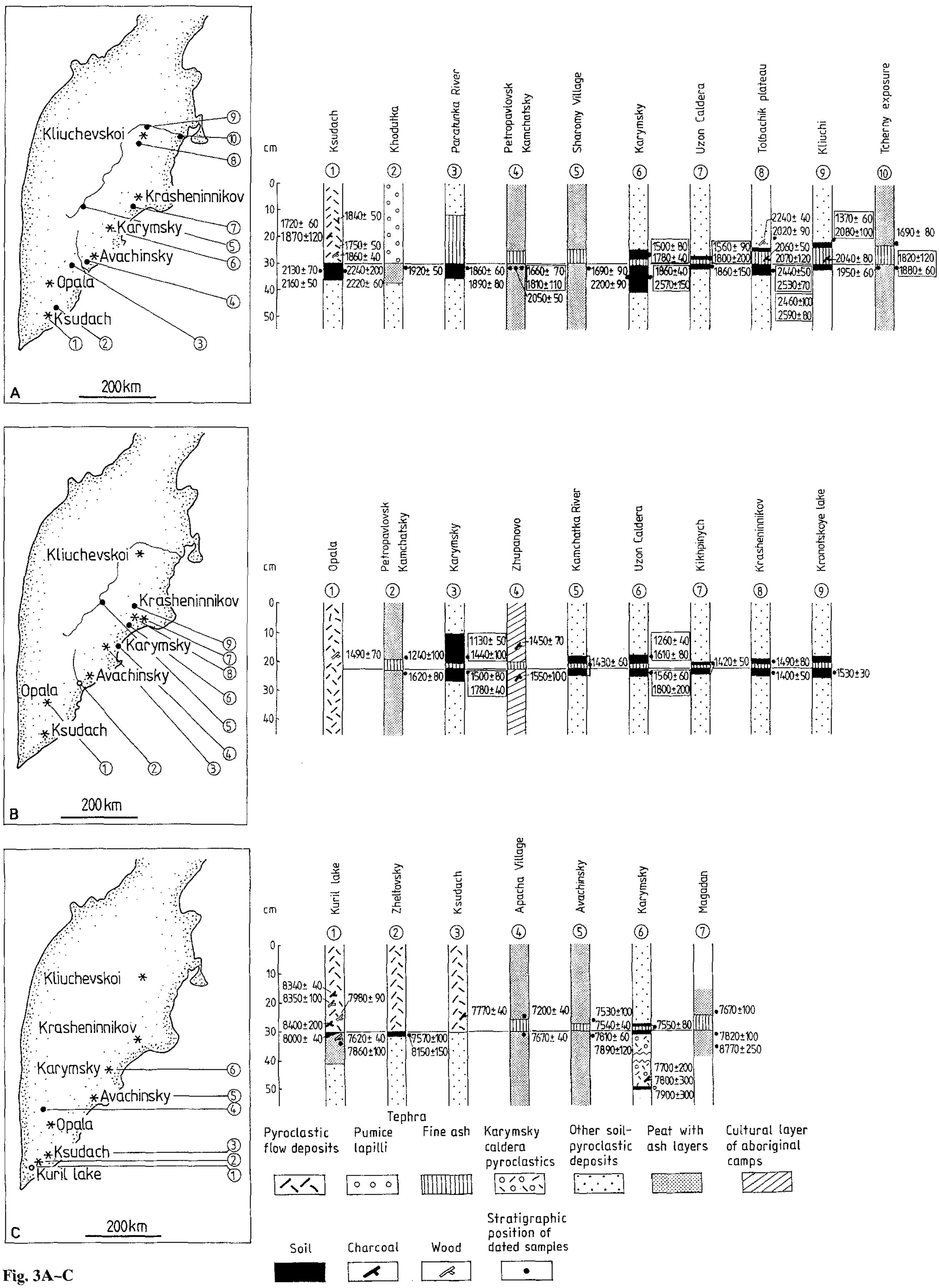
A
200km
Kliuchevskoi
Krasheninnikov
Karymsky
Avachinsky
Opala
Ksudach
cm
Ksudach
Khodutka
Paratunka River
Petropavlovsk Kamchatsky
Sharomy Village
Karymsky
Uzon Caldera
Tolbachik plateau
Kliuchi
Tcherny exposure
B
200km
Opala
Petropavlovsk Kamchatsky
Karymsky
Zhupanovo
Kamchatka River
Uzon Caldera
Kikhpinych
Krasheninnikov
Kronotskoye lake
C
200km
Kuril lake
Kuril lake
Zheltovsky
Ksudach
Apacha Village
Avachinsky
Karymsky
Magadan
Tephra
Pyroclastic flow deposits
Pumice lapilli
Fine ash
Karymsky caldera pyroclastics
Other soil-pyroclastic deposits
Peat with ash layers
Cultural layer of aboriginal camps
Soil
Charcoal
Wood
Stratigraphic position of dated samples

Fig. 3A–C

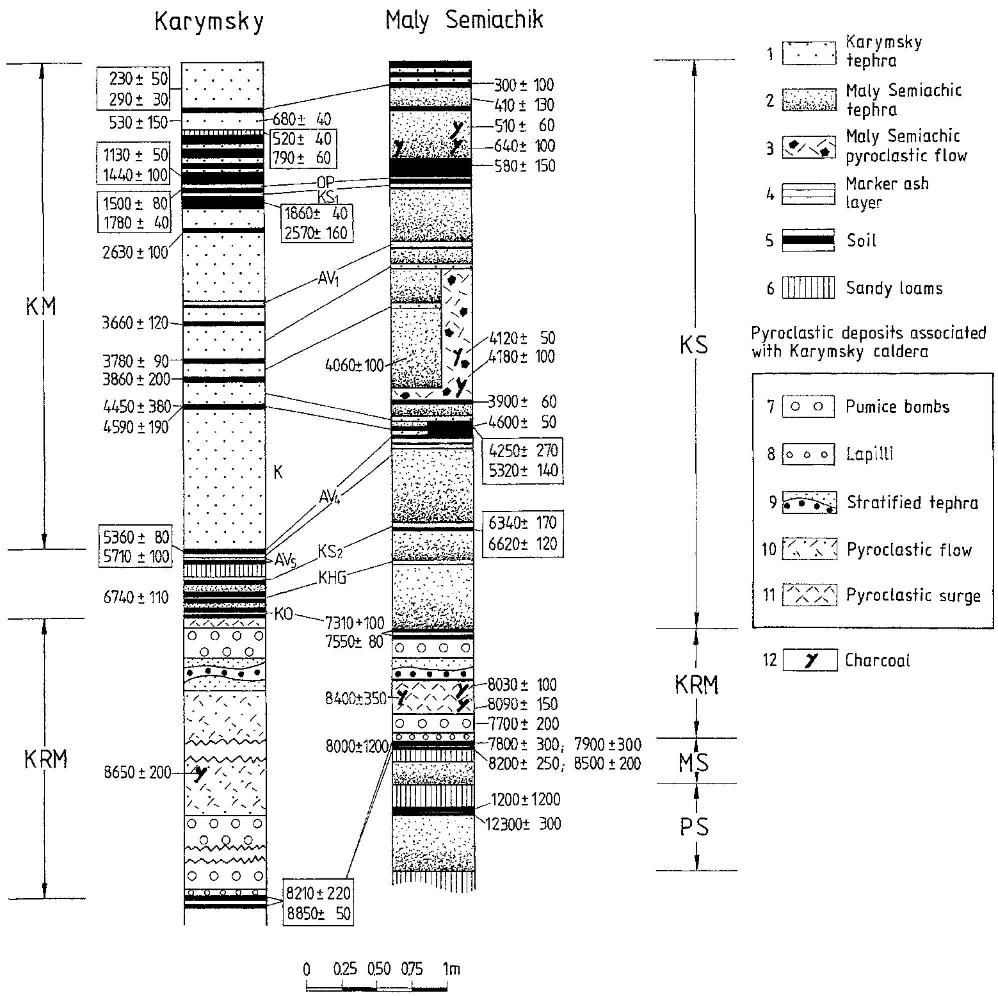

Fig. 4 Generalized sections through soil–pyroclastic sequence at the foot of Karymsky and Maly Semiachik volcanoes. **1**, Tephra from Karymsky; **2**, tephra from Maly Semiachik; **3**, pyroclastic flow deposits of Maly Semiachik; **4**, marker ash layers; **5**, buried soil horizons; **6**, slightly humic sandy loams; **7–11**, pyroclastic deposits associated with the formation of Karymsky caldera – **7**, pumice bombs; **8**, pumice lapilli; **9**, stratified tephra; **10**, pyroclastic flow; **11**, pyroclastic surge; and **12**, charcoal

Tephrostratigraphic studies also indicate that fine ash from the Kuril Lake eruption exposed in the Karymsky volcano region lies above the Karymsky caldera pyroclastic deposits and is intercalated between the above-mentioned soils dated 7550 ± 80 (Fig. 3C). Thus the Kuril Lake caldera is younger than the Karymsky caldera and formed roughly 7600–7700 years ago.

Similar dates of 7670 ± 100 and 7820 ± 100 years have been obtained on soils respectively over- and underlying the Kuril Lake tephra near Magadan city, more than 1000 km north-west of the source (Melekestsev et al. 1991b).

Iliinsky caldera , within which Iliinsky volcano is located, is immediately adjacent to the Kuril Lake from the east. It formed immediately alter the Kuril Lake caldera collapse as its pyroclastic deposits directly overlie those of the Kuril Lake.

Calderas of the Ksudach volcanic massif

All Holocene calderas at Ksudach volcano have been dated. The oldest (caldera III) was identified by Selyangin (1990) and formed, according to our data, 8700–8800 years BP as a result of the KS_4 eruption. The dates on a thin carbonized soil underlying the pyroclastics from that eruption range from 8770 to 8870 years (Table 3).

The second Holocene caldera (caldera IV) at Ksudach volcano formed roughly 6000 years BP as a result of two closely spaced explosive eruptions, KS_2 and KS_3. In most sections, the pyroclastic layers from these eruptions directly overlie each other. Only in rare instances does a thin layer of slightly humic sandy loams occur between them. This suggests that the pyroclastic units correspond to two different eruptions separated by a short time interval. The caldera-forming eruptions KS_2 and KS_3 took place 6000 and 6100 years BP, respectively. The date of 6130 ± 40 years was obtained under the KS_3 pyroclastic unit, which coincides with the date of 6130 ± 70 from the humic layer separating the KS_3 and KS_2 units. The dates from thin soils underlying the KS_2 unit range from 5790 to 6130 years (Table 3) and the age of the soil overlying the ash of this eruption is 5970 ± 100 years. These data suggest that the eruption occurred about 6000 years BP.

Older ages shown in Table 3 (6200–6500 years) were obtained from soil underlying the KS_2 tephra at long distances from the Ksudach massif near the Maly and

Fig. 3 Radiocarbon dates for the pyroclastic deposits KS_1 from Ksudach (caldera V) (**A**); OP from Baraniy Amphiteatr crater (**B**); KO from Kuril Lake caldera (**C**)

Table 3 Ages of Holocene calderas and craters of subcaldera eruptions

Names of calderas and craters	^{14}C dates (years)	Laboratory index	Comments	^{14}C ages (years)
Calderas				
Karymsky	7550 ± 80	GIN-1047	bs^{1}	7700–7800
	7700 ± 200	GIN-844	c^{2}	
	7800 ± 300	GIN-1049	bs^{3}	
	7900 ± 300	GIN-1163	bs^{3}	
	7920 ± 70	GIN-5278	bs^{3}	
	8030 ± 100	GIN-1171	c^{2}	
	8090 ± 150	GIN-1162a	c^{2}	
	8400 ± 350	GIN-1162	c^{2}	
	8650 ± 200	IVAN-519	c^{2}	
Kuril Lake	7530 ± 100	IVAN-812	bs^{1}	7600–7700
	7540 ± 40	GIN-6338	bs^{1}	
	7550 ± 80	GIN-1047	bs^{4}	
	7570 ± 100	IVAN-828	bs^{3}	
	7620 ± 40	GIN-1062	w^{3}	
	7670 ± 40	GIN-5252	p^{3}	
	7670 ± 100	GIN-6085	bs^{1}	
	7770 ± 40	GIN-5689	c^{2}	
	7810 ± 60	IVAN-822	p^{3}	
	7820 ± 100	GIN-6079	p^{3}	
	7860 ± 100	GIN-1063	p^{3}	
	7890 ± 120	GIN-6340	p^{3}	
	7980 ± 90	GIN-1061	w^{2}	
	8000 ± 40	GIN-207	bs^{3}	
	8150 ± 150	IVAN-826	bs^{3}	
	8340 ± 40	GIN-211	c^{2}	
	8350 ± 100	GIN-728	w^{2}	
	8400 ± 200	GIN-1060	c^{2}	
Ksudach				
Caldera III	8770 ± 80	GIN-5686	bs^{3}	8700–8800
	8820 ± 50	GIN-2984	bs^{3}	
	8870 ± 60	IVAN-833	bs^{3}	
Caldera IV	5970 ± 100	GIN-1176	bs^{1}	6000
	5790 ± 120	GIN-5679	bs^{3}	
	5930 ± 70	IVAN-869	p^{3}	
	6090 ± 100	GIN-1175	p^{3}	
	6130 ± 70	IVAN-802	bs^{3}	
	6130 ± 40	GIN-5685	bs^{3}	
	6200 ± 40	GIN-4431	p^{3}	
	6340 ± 170	IVAN-281	bs^{3}	
	6360 ± 60	GIN-5268	p^{3}	
	6500 ± 110	IVAN-712	p^{3}	
Caldera V	1660 ± 70	IVAN-397	p^{3}	1700–1800
	1690 ± 80	GIN-6321	p^{1}	
	1690 ± 190	IVAN-705	p^{3}	
	1720 ± 60	GIN-2959	c^{2}	
	1750 ± 50	GIN-2975	w^{2}	
	1780 ± 40	IVAN-191	bs^{1}	
	1800 ± 200	GIN-328	bs^{1}	
	1820 ± 120	IVAN-450	p^{3}	
	1840 ± 50	GIN-2974	c^{2}	
	1860 ± 40	GIN-2975a	w^{2}	
	1860 ± 40	IVAN-193	bs^{3}	
	1860 ± 60	GIN-3156	bs^{3}	
	1860 ± 150	IVAN-331	bs^{3}	
	1870 ± 120	GIN-2959a	c^{2}	
	1890 ± 80	IVAN-639	p^{3}	
	1920 ± 50	GIN-2991	p^{3}	
	1950 ± 60	IVAN-556	bs^{3}	
	2020 ± 90	IVAN-70	bs^{1}	
	2040 ± 80	IVAN-121	c^{2}	
	2040 ± 200	GIN-2980	bs^{3}	
	2050 ± 50	GIN-1180	p^{3}	
	2060 ± 50	GIN-1858	c^{2}	

Table 3 (Continued)

Names of calderas and craters	^{14}C dates (years)	Laboratory index	Comments	^{14}C ages (years)
	2070±120	IVAN-57	c^2	
	2130± 70	GIN-2959	bs^3	
	2220± 60	GIN-2976	bs^3	
	2240±110	IVAN-36	c^1	
	2440± 50	IVAN-82	bs^3	
Tao-Rusyr	7500± 80	KSM-438 III	c^2	7500
Lvinaya Past	9400± 60	GIN-325	c^2	9400
Craters				
Baraniy Amfiteatr (Opala volcano)	1400± 50	IVAN-317	bs^3	1400–1500
	1420± 50	IVAN-372	bs^4	
	1430± 60	IVAN-467	bs^4	
	1440±100	IVAN-189	bs^1	
	1450± 70	IVAN-171	c^1	
	1490± 80	IVAN-316	bs^1	
	1490± 70	GIN-1034	c^2	
	1500± 80	IVAN-191	bs^3	
	1530± 30	GIN-3026	bs^3	
	1550±100	IVAN-172	c^3	
	1560± 90	IVAN-328	bs^3	
	1610± 80	IVAN-323	bs^1	
	1620± 80	IVAN-399	p^3	
Khodutkinsky 'Maar'	2800± 40	GIN-4934	p^3	2800
	2850±120	GIN-2291	p^3	
	2960±120	GIN-4935	p^3	
Khangar	6740± 70	IVAN-573	c^1	6900–7000
	6850± 90	IVAN-86	w^3	
	6910±120	GIN-3028	c^2	
	6930± 80	GIN-5289	p^3	
	6960± 80	IVAN-319	c^2	
	7040±170	GIN-5270	p^3	
	7080±170	IVAN-688	bs^3	
	7080±120	IVAN-228	bs^3	
	7140±100	GIN-5288	p^1	
	7150± 80	IVAN-692	bs^1	

Notes: c, charcoal; w, wood; p, peat; and bs, buried soil. Indices in column 4 show the stratigraphic position of the dated organic matter: 1, 2, 3, respectively, over, in and under the pyroclastic deposits; and 4, soil or peat enclosing tephra layer. Indices of Laboratories: IVAN, Institute of Volcanic Geology and Geochemistry, Petropavlovsk-Kamchatsky; GIN, Geological Institute, Moscow; KSM, Geochemical Institute, Moscow. Dates which were too old to be used for age estimations are separated by a blank line; see explanations in the text.

Bolshoy Semiachik volcanoes and in the Uzon caldera. Although there is no unambiguous explanation of this, the peat and soil layers may have formed over a long period of time and the dates obtained represent the average values for the whole layer rather than for its upper part.

The date of 4910±300 years (GIN-2978, for explanation of laboratory indices see Table 3) from under the pyroclastics KS_2 (Melekestsev and Sulerzhitsky 1990) is significantly younger and contradicts the whole series of dates obtained. The invalidity of this date is supported by data implying that the ash KS_2 lies in sections below the ash from the Avachinsky volcano, with the age of 5400–5500 years (Fig. 7).

The third Holocene caldera (caldera V) formed 1700–1800 years ago. The tephra from this eruption (KS_1) is traced for more than 1000 km north of the caldera. Earlier (Piyp 1956; Gushchenko 1965; Braitseva et al. 1984, 1989b), this tephra north of Kronotskoe Lake was mistakenly associated with the Shiveluch eruption (designated by index SH_4). However, ensuing detailed studies in the region of Shiveluch volcano and direct field correlation have demonstrated that this tephra is a fine ash (KS_1) from the caldera-forming eruption of Ksudach volcano. At present, about 30 dates are available for pyroclastic deposits related to that eruption (Fig. 3A, Table 3). Dates ranging from 1720 to 1870 BP have been obtained on charcoal and wood in pyroclastic flow deposits near the caldera. Dates obtained on the soil and peat underlying the caldera pyroclastics and tephra range from 1660 to 2400 years BP; the younger of them (1660–1890 BP) are in good agreement with the above-mentioned dates on charcoal and wood. Dates ranging from 1690 to 1800 BP on the soil and peat overlying tephra KS_1 also indicate that the eruption took place 1700–1800 BP. When the soil underlying the tephra (sections 1, 4 and 6 in Fig. 3A) gives older ages (2000–2200 BP), it must have been

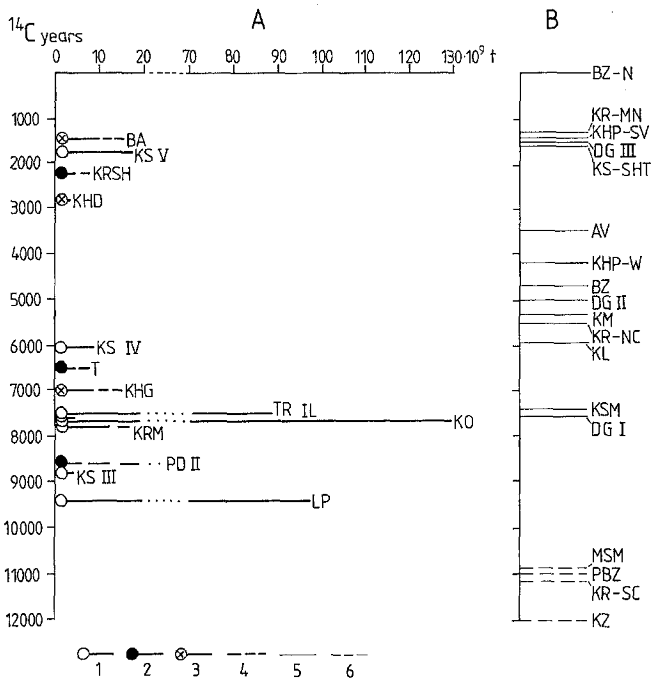

Fig. 5 Age and mass of erupted products of Holocene caldera-forming and subcaldera eruptions (**A**) and onset of the formation of active volcanoes (**B**). **1,** Krakatoa-type caldera-forming eruptions and related mass of pyroclastics; **2,** eruptions resulted in Hawaiian-type calderas; **3,** subcaldera eruptions; **4,** presumed mass of ejecta; **5** and **6,** onset of active volcanoes formation – **5,** established; **6,** assumed. Indices: BA, Baraniy Amfiteatr crater (Opala volcano); KS, calderas of Ksudach massif; KRSH, caldera on Krasheninnikov volcano; KHD, Khodutkinsky 'Maar' crater; T, Plosky Tolbachik caldera; KHG, Khangar crater; TR, Tao-Rusyr caldera; KO, Kuril Lake caldera; IL, Iliinsky caldera; KRM, Karymsky caldera; PD II, Plosky Dalny II caldera; and LP, Lvinaya Past' caldera. Volcanoes: BZ, Bezymianny; BZ-N, Novy Dome; PBZ, Pre-Bezymianny; Krasheninnikov volcano: KR-MN, Mid North cone; KR-NC, North cone; KR-SC, South cone; Kikhpinych volcano: KHP-SV, Savich cone; KHP-W West cone; DG, Dikiy Greben; KS-SHT, Shtyubel cone; KZ, Kizimen volcano; AV, young cone of Avachinsky volcano; KM, Karymsky; KL, Kliuchevskoi; KSM, Kaino-Semiachik; and MSM, Meso-Semiachik

formed over a long period of time and the dates obtained show the mean age of the whole soil horizon. We note that dates in sections 8 and 9 differ. Dates of about 2000 BP and older have been obtained here on soils not only underlying the ash, but also overlying it, as well as on charcoals and wood. Just within the Kliuchevskoi volcano group the age of this ash, previously called SH_4, was derived to be roughly 2000 BP (Braitseva et al. 1984). However, outside the Kliuchevskoi volcano group further north-east, we again obtain dates of 1700–1800 years BP for the same ash (section 10). The reason for the older ages in the region of the Kliuchevskoi volcano group remains obscure.

Ages were also determined for several large Holocene 'Hawaiian-type' calderas formed in Kamchatka. The younger caldera at the summit of Plosky Dalny is associated with the formation of large lava flows and cinder cones at the foot of the volcano (Lavovy Shysh cone group) and its age is roughly 8600 years. Lavas from these eruptions overlie the moraine of stage II of the Late Pleistocene glaciation; the age of soil underlying the pyroclastics from these eruptions is 8610±60 (GIN-7403) and the age of soil overlying it is 8620±100 years (IVAN-674). The caldera at Plosky Tolbachik apparently formed about 6500 years ago as a response to profuse lava outflows and subsynchronously with a large sector collapse at Ostry Tolbachik volcano (Melekestsev and Braitseva 1988). The associated debris avalanche deposits lie in a soil–pyroclastic sequence above the marker ash KHG, with an age of 6900–7000 years. The caldera at the North cone of Krasheninnikov volcano formed about 2200–2400 years ago as a result of large eruptions of andesitic lavas and tephra (Ponomareva 1990). The dates of 2240±60 (GIN-3023) and 2440±70 years (IVAN-318) were obtained for soil separating these tephra units.

Two 'Krakatoa-type' calderas formed in the Holocene in the Kuril Islands. Tao-Rusyr caldera formed roughly 7500 years ago as a series of radiocarbon dates, the youngest of which is 7500±80 years, were obtained on charcoals from pyroclastic flow deposits associated with this caldera (Melekestsev et al. 1974b). The latter are underlain by the Kuril Lake tephra aged 7600–7700 years BP (Table 2). Lvinaya Past' caldera apparently formed about 9400±60 years BP, as indicated by a date on charcoal from a pyroclastic unit produced by the caldera-forming eruptions.

Craters of subcaldera eruptions

In Kamchatka there are three large craters that produced large volumes of pyroclastics comparable with those of the caldera-forming eruptions. The pyroclastic deposits include pyroclastic flows and tephras that can be traced for tens and hundreds of kilometers. At the final stage of such eruptions, extrusive domes commonly grow within the craters. Such craters have no distinct signs of coffapse and may be located either near the base of the volcanoes or at their summits. The eruptions that resulted in the formation of such craters were named 'subcaldera eruptions' (Melekestsev et al. 1991a). An historical analog to such eruptions is the Novarupta eruption of 1912.

Baraniy Amfiteatr crater (1.3×2 km, Fig. 8) formed as a result of the great eruption which produced more than 10 km^3 of rhyolite pyroclastic material about 1400–1500 years BP (Melekestsev et al. 1991a). The crater is located at the foot of Opala volcano. Carbonized wood from the pyroclastic deposits in the proximity of the crater was dated as 1490±70 years (Sheimovich and Patoka 1979). Soils buried by tephra from that eruption yielded ages of 1400–1560 years and soils overlying this tephra 1440–1490 years (Fig. 3B, Table 3). The dates of 1610±80 from under the tephra and 1240±100 (IVAN-400) from above it (section 2, Fig. 3B) seem to show the mean age of thick peat layers and

Fig. 6 Holocene Karymsky caldera and the younger Karymsky volcano. Late Pleistocene Karymsky Lake caldera and Upper Pleistocene dissected pyroclastic cover are in the background. View to south. Photo by V. A. Podtabachny

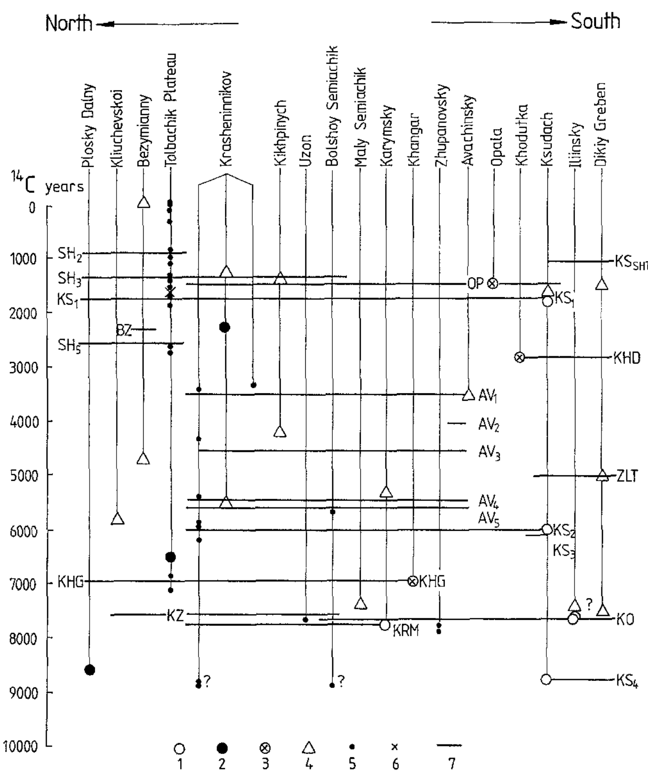

Fig. 7 Ages of Holocene stratovolcanoes, calderas and craters of subcaldera eruptions and monogenic forms of Kamchatka and their correlation with tephra marker layers. **1,** Krakatoa-type calderas; **2,** Hawaiian-type calderas; **3,** craters of subcaldera eruptions; **4,** stratovolcanoes (onset of their formation); **5,** monogenic forms (cinder cones, extrusive domes, maars); **6,** onset of supply of magnesian basalts in the Tolbachik zone of cinder cones; and **7,** tephra marker layers (see indices in Table 2, lines for ashes correspond to the true area of their dispersal)

show, respectively, older and younger ages. An age on charcoal from the cultural layer of aboriginal camps in the settlement of Zhupanovo over the Baraniy Amfiteatr ash layer is 1450±70 and, under this ash, 1550±100 years (Braitseva et al. 1987).

Khodutkinsky Maar crater, with a diameter of 0.9 km, is located at the base of Khodutkinsky volcano. The eruption associated with this crater produced more than 1 km^3 of rhyolite–dacite pumice pyroclastics. The crater age is about 2800 years based on three dates on peat and soil underlying tephra from that eruption (Table 3).

A large crater (2.5×2 km) at the summit of Khangar volcano is also a result of a subcaldera eruption. The total volume of dacite pyroclastic deposits produced by this eruption, including tephra and pyroclastic flows, was probably more than 10 km^3. Charcoal ages from pyroclastic flows produced by that eruption were 6460±135 years (MO-169, Braitseva et al. 1974). In recent years, numerous new dates have been obtained for tephra from that eruption, which suggest the age of the Khangar crater to be 6900–7000 years. Charcoals from the ash layer as well as peat and soils underlying it yield ages of 6850–7080 years (Table 3). Carbonaceous interbeds, soils and peat over this ash have ages 6740±70, 7150±80 and 7140±100 years.

Holocene stratovolcanoes

The ages of Holocene stratovolcanoes (Figs 1B, 5 and 9) were obtained through detailed geological and tephrochronological studies which included: (1) mapping of volcanic landforms; (2) measuring of soil–pyroclastic sections and compiling a summary section through the Holocene tephra deposits; and (3) dating of all mapped landforms (lava and pyroclastic flows, debris aval-

Fig. 8 Opala volcano and Baraniy Amfiteatr crater. View to north-west. Photo by V. N. Dvigalo

anches, etc.) through the study of the overlying tephra layers and compiling a summary section including all the deposits of a volcano. Then, the eruptive history of a volcano being reconstructed, we can identify the deposits of the earliest eruptions of each cone and date them by the radiocarbon method on associated organic matter (Table 4), or by correlation with the tephra marker beds (Fig. 7).

The age of Kliuchevskoi (Fig. 10) was previously reported to be about 6100 years based on the rate of soil–pyroclastic cover accumulation between the cinder from its earliest eruptions and dated marker ash layers (Melekestsev et al. 1990). New radiocarbon dates (Table 4) suggest that Kliuchevskoi volcano began to form between 5800 and 6000 years BP.

The age of Bezymianny stratovolcano is about 4700 years, as shown by the position of tephra from its earliest eruptions in soil–pyroclastic sequences between dated marker ashes from Shiveluch (SH_5) and Khangar (KHG) volcanoes (Braitseva et al. 1991). The approximate age of the volcano was determined using the calculated rate of sandy loam accumulation between these marker ashes. An older pre-Bezymianny volcano, a fragment of which was preserved in the south-eastern part of the edifice, formed about 11000 years ago and stopped its activity about 7000 years ago. Its tephra was found in a soil–pyroclastic sequence within the interval between the base of the section with a date of 10700±200 years and marker ash KHG (6900–7000 years BP). Of special interest is the Novy dome, which started to grow in the crater of Bezymianny after its well-known eruption of 1955–1956. We consider the Novy dome as the third volcano, or 'Neo-Bezymianny'. The style of its activity (high explosive activity, repeated lava outflows and very high production rate) is typical of the onset of stratovolcano formation (Braitseva et al. 1991), which suggests that this is the initial phase of a new large andesitic volcano, rather than the growth of a typical (small) extrusive dome. It is noteworthy that this volcano started to form after a prolonged repose period lasting for about 1000 years.

Kizimen volcano started to form at the boundary between the Late Pleistocene and Holocene. Pyroclastic flow deposits from one of the first large eruptions of this volcano lie at the base of the Holocene soil–pyroclastic sequence immediately on the moraine deposits of stage II. Dates obtained in the section above these pyroclastics are 9190±150 and 8940±150 years. However, study of sections of the volcano demonstrates that the eruption of this pyroclastic flow was preceded by a period of intensified activity with outpourings of lava and block and ash flows and the growth of an extrusive dome, which suggests that this volcano started to form at the end of the Late Pleistocene, roughly 11000–12000 years ago (Melekestsev et al. 1995).

Estimates of age were made for three edifices that make up the massif of Krasheninnikov volcano (Ponomareva 1990). The South cone began to form no later than 11000 years ago, as cinders produced during the earliest stages of its activity are intercalated in the moraine deposits of stage II and immediately overlie them. A date of 9320±40 years was obtained on peat in the section substantially stratigraphically higher than these cinders. The South cone activity ended about 6500 years ago, as tephra from its most recent eruption lies between marker ash KHG and peat with an age of 6200±40 years.

The North cone started to form 5500 years ago based on dates obtained from peat and soil immediately beneath and over the cinders from its earliest eruption (Table 4) and confirmed by their stratigraphic position between the marker ashes from Avachinsky volcano (AV_4 dated at 5400–5500 years and AV_5 dated at 5600 years, Table 2, Fig. 7).

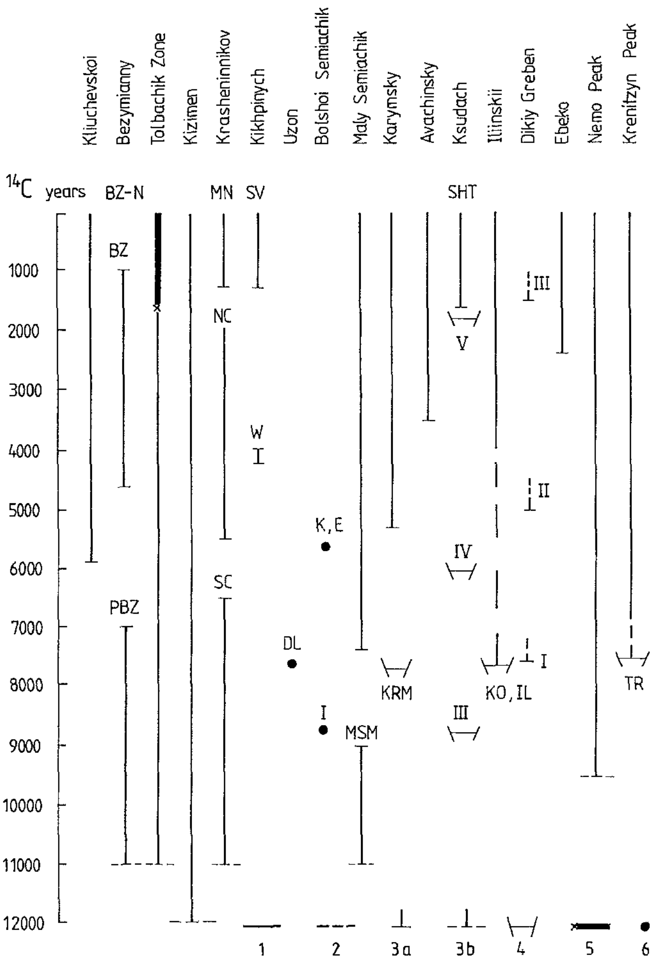

Fig. 9 Ages of Holocene volcanoes and calderas. **1-2,** Period of volcano formation: **1,** established; **2,** assumed; **3,** onset and end of volcano formation (horizontal lines) – **a,** established; **b,** assumed; **4,** calderas; **5,** time of intense supply of magnesian basalts and large cinder cone formation in the Tolbachik zone; and **6,** monogenetic eruptive centers. Indices: DL, Dalnee Lake maar; extrusive domes – I, Ivanov; K, Korona; and E, Ezh. Other indices as in Fig. 5

The Mid-North cone located inside the North cone summit caldera formed about 1300 years ago. This is supported by the date of 1300±120 years obtained on charcoal immediately under cinders from the earliest eruptions of the cone, as well as by the stratigraphic position of volcanics from these eruptions immediately over the marker ash SH_3 with an age of 1300–1400 years (Fig. 7).

Young Kikhpinych volcano formed in the mid-Holocene and is separated from the ancient extinct Old Kikhpinych (Mount Peak) by a repose period which lasted for a few tens of thousands of years. The radiocarbon age of the first West cone was taken to be 4000 years (Braitseva et al. 1989a). New dates of 4240±40 years obtained on peat under the pyroclastic deposits of this cone and 4080±50 on soil over them suggest that the cone formed within a 200 year period between 4200 and 4000 years ago. The second cone, Savich cone, began to form 1400 years ago after nearly more than a 2500 year repose period. This is supported by the dates obtained on soils buried by pyroclastics from its earliest eruptions (Table 4) and by the stratigraphic position of this pyroclastic unit between the marker ashes SH_3 and OP (Table 2, Fig. 7). Fumarolic activity at Savich cone is still observed.

Detailed tephrochronological studies (Braitseva et al. 1980) allow an age determination of all three cones of Maly Semiachik volcano. The first cone, Paleo-Semiachik, began to form about 20000 years ago, as estimated from the average production rate of the volcano (Selyangin et al. 1979). Pyroclastic deposits from three Maly Semiachik cones (PS, Paleo-Semiachik; MS, Meso-Semiachik; and KS, Kaino-Semiachik), can be seen in the soil–pyroclastic sequence at the base of Maly Semiachik volcano (right column, Fig. 4). Buried soils fix the periods of repose between the formation of these cones (Figs 2 and 4). Paleo-Semiachik ceased its activity earlier than 12000 years ago, which is supported by the dates from the soils overlying its pyroclastic deposits (Table 4). The middle Meso-Semiachik cone began to grow about 11000 years ago as its pyroclastic deposits overlie the above-mentioned 12000 year old soils, and completed its activity about 9000 years ago. The date of 8500±200 years was determined on the soil horizons overlying its pyroclastics. The youngest Kaino-Semiachik active cone formed 7300–7400 years ago based on the dates from the soil underlying the pyroclastic deposits from its earliest eruptions (Table 4). These pyroclastics lie between the marker tephra layers KHG and KO (Table 2), closer to the latter.

Karymsky volcano (Fig. 6) began to form within the Karymsky caldera about 5300 years ago (Braitseva and Melekestsev 1991). The profuse pumice pyroclastic unit KRM associated with the formation of the caldera can be seen in the soil–pyroclastic sequence (Figs 2 and 4). This pyroclastic unit is overlain by a thick package of soils that contains thin marker ashes and records a 2400 years long period of quiescence after the caldera-forming eruption. These soils are overlain by the pyroclastic deposits KM from Karymsky volcano, which formed inside the caldera; the layer K is tephra from its earliest eruptions. The youngest dates for soils underlying layer K are 5280±120 and 5360±80 years. This is in good agreement with the position of this layer immediately over the marker ash AV_4 (Table 2, Fig. 7) dated at 5400–5500 years.

The yound cone of Avachinsky volcano started to form about 3500 years ago. Charcoals from pyroclastic flow and surge deposits of this eruption have an age of 3570±40 and 3510±100 years, and dates for buried soils underlying these deposits are 3560±50 and 3580±90 years. The marker tephra layer AV_1 (Table 2) is associated with the earliest eruption of the young cone of Avachinsky volcano.

Gorely volcano probably started to form during the second stage of the Late Pleistocene glaciation. This is based on the atypically great thickness and specific

Table 4 Radiocarbon dates for the onset and completion of the Holocene volcanic cones formation in the Kurile-Kamchatka region

Volcano	^{14}C dates (years)	Laboratory index	Comments	^{14}C ages (years)
Kliuchevskoi	> 5760 ± 50	GIN-7810	bs	5800–6000
	< 6000 ± 100	GIN-7814a	bs	
Bezymianny	> 2500 ± 170	IVAN-128	bs	~4700
	< 7080 ± 120	IVAN-228	bs	
Pre-Bezymianny	10700 ± 200	IVAN-13	bs	11000?–7000*
Kizimen	> 9190 ± 150	IVAN-394	bs	12000–11000
	> 8940 ± 150	IVAN-308	bs	
Krasheninnikov				
Mid-North cone	1300 ± 120	IVAN-313	c	1300
North cone	5510 ± 80	IVAN-305	bs	5500
	5550 ± 50	GIN-4429	p	
	5580 ± 40	GIN-4430	p	
South cone	> 6200 ± 40 +	GIN-4431	p	11000—6500*
	< 6910 ± 120 +	GIN-3028	c	
Kikhpinych				
Savich cone	1420 ± 50	IVAN-372	bs	1400
	1490 ± 80	IVAN-316	bs	
West cone	4080 ± 50 +	GIN-4421	bs	4200—4000*
	4240 ± 40	GIN-4425	p	
Maly Semiachik				
Kaino-Semiachik	7310 ± 100	GIN-1055	bs	7300–7400
	7550 ± 80	GIN-1047	bs	
Meso-Semiachik	> 8500 ± 200 +	GIN-1048	bs	11000–9000*
	< 12000 ± 1200	GIN-1376	bs	
	< 12300 ± 300	GIN-1375	bs	
Paleo-Semiachik	12000 ± 1200 +	GIN-1376	bs	20000?–12000*
Karymsky	5280 ± 120	IVAN-179a	bs	5300
	5360 ± 80	IVAN-178a	bs	
Avachinsky				
Young cone	3510 ± 100	IVAN-815	c	3500
	3570 ± 40	GIN-6056	c	
	3560 ± 50	GIN-6361	bs	
	3580 ± 90	IVAN-843	bs	
Ksudach				
Shtyubel cone	> 1490 ± 70	GIN-1034	c	1600
	< 1750 ± 50	GIN-2975	w	
Iliinsky				
Yound cone				< 7600–7700
Dikiy Greben				
Stage II	1600 ± 30	GIN-8120	bs	1600
	1600 ± 40	GIN-8118	w	
	1620 ± 40	GIN-8117	w	
Stage II	5020 ± 50	GIN-4931	c	~5000
Stage I				< 7600–7700
Ebeko	2270 ± 60	IVAN-931	p	2300–2400
	2410 ± 60	GIN-6064	p	
Nemo Peak	> 9050 ± 100	GIN-5323	bs	~9500
	> 9130 ± 140	GIN-5311	bs	
Krenitsyn Peak	< 7500 ± 80	KSM-438III	c	< 7500

All ^{14}C dates are given for the onset of volcano formation, except for the dates with sign $^{+}$, which indicates the completion of cone formation. Ages with sign * designate the end of cone life; the rest imply the onset of volcano formation (see text). Other symbols as in Table 3.

morphology of very high and steep frontal cliffs of basaltic–andesite lava flows from the earliest eruptions, which are probably due to ponding against the glacier.

Shtyubel cone in caldera V of Ksudach massif began to form about 1600 years ago. Tephra from its earliest eruptions lies between the KS_1 pyroclastic deposits (1700–1800 years) and the ash marker bed OP dated at 1400–1500 years (Fig. 7). The large crater at the summit of Shtyubel cone first formed 1000–1100 years ago during an eruption that produced more than 1 km^3 of tephra (KS-SHT, Table 2). Radiocarbon dates for peat and carbonized soil under tephra from this eruption are

Fig. 10 Kliuchevskoi volcano and cinder cones of its flank eruptions. Bezymianny volcano with its fume cloud is on the distant left. View to southwest. Photo by V. A. Podtabachny

1010±60 (GIN-4936), 1090±100 (GIN-4926) and 1110±40 years (GIN-4933). Crater activity was renewed during a smaller eruption about 300 years ago and it finally gained its modern shape as a result of a violent explosive eruption in 1907.

The young cone of Iliinsky volcano began to form not earlier than 7600–7700 years ago, as it is located in Iliinsky caldera of roughly the same age. A large explosive crater on the east flank of the volcano may have formed later than 200 years ago. The date of 180±40 years (GIN-4924) determined for soil underlying its deposits does not exclude the possibility that this was the eruption witnessed in 1901 (Novograblenov 1932).

Tephrochronological studies allow us to refine the earlier interpretation of Masurenkov (1980b) on two episodes of the Dikiy Greben volcano formation. Our studies suggest that this eruptive center located near the Kuril Lake caldera consists of a number of large extrusive domes emplaced during three short phases of activity separated by long repose periods. Its earliest eruptions (DG I stage) took place about 7600–7700 years BP, immediately after the Kuril Lake caldera collapse, as their fallout directly overlies the pyroclastic flows associated with this caldera. The second phase of activity (DG II) took place about 5000 years ago, which is supported by the position of its pyroclastic deposits at the stratigraphic level close to that of marker ash bed ZLT (Table 2). The largest part of the Dikiy Greben edifice, including profuse lava flows descending to the north and south from its summit (Mount Nepriyatnaya), formed about 1600 years ago (stage DG III), based on the dates on wood and soil buried by the pyroclastic surge deposits of this eruption (Table 4).

Estimates were made for the ages of three volcanoes in the northern Kuril Islands: Ebeko in Paramushir and Peak Nemo and Peak Krenitsyn in the Onekotan Island. Ebeko formed 2300–2400 years ago; radiocarbon dates for tephra from its earliest eruptions are 2270±60 and 2410±60 years. Peak Nemo started to form at the beginning of Holocene, about 9500 years ago. Tephra from its earliest eruptions is older than the overlapping buried soils dated at 9050±100 and 9130±140 years. Peak Krenitsyn is younger than 7500 years, which was determined from its position within the Tao-Rusyr caldera of roughly the same age.

Monogenetic volcanoes

A large cinder cone and related basaltic lava field (approximately 100 km^2) on the east flank of the Sredinny Ridge in the upper reaches of the Right and Left Ozernaya rivers formed in early Holocene time. Lava flows overlying moraine deposits are covered with a soil–pyroclastic sequence of the entire Holocene period. The lowermost marker horizon in this sequence is the ash KHG dated at 6900–7000 years, which rests on a 15 cm layer of eolian sandy loam.

We have established the general age progression for the largest cinder cones in the Tolbachik regional zone located immediately to the south of Tolbachik volcano (Fig. 1). The sequence of stages of volcanic unrest has been determined and a map of cinder cones and lava flows in the Tolbachik plateau has been compiled, specifying the age of volcanics in thousands of years (Braitseva et al. 1984; see revision of SH_4 age in the present paper). Cones of stage I were built between 1800 and 10000 years ago. Cones of stage II are younger than 1800 years; among them are the largest cinder cones of the regional zone. Pelmen, Mount 1004 and Pre-Vysokaya were initiated between 1500 and 1800 years ago; Peschanye Gorki, Alaid, Kleshnya and Mount Vysokaya formed in a sequence immediately after each other within a short time interval 900–1000 years ago. The youngest prehistoric cone is Zvezda cone, with an age of a few hundred years.

Estimates were made for the age of many monogenetic volcanoes of East Kamchatka (Figs 7 and 9). The small monogenetic Sopochka Duga volcano, located between Uzon and Krasheninnikov calderas, formed about 3200–3300 years ago; its tephra overlies the ash marker bed AV_1 dated at 3500 years; over this tephra a date of 2990±40 years (GIN-3022) has been obtained. Ages determined for some volcanic forms north of Krasheninnikov volcano are as follows (Ponomareva 1990): Krokur maar formed about 4300 years ago (a date obtained on soil underlying its deposits is 4320±110 years (GIN-3020); Zametny cone was built about 3400 years ago (its deposits immediately underlie tephra from Sopochka Duga). A large maar (Dalnee Lake) formed in Uzon caldera in Holocene times. It is dated at about 7600–7700 years; its cinders lie between the tephra marker layers KRM (7700–7800 years) and KZ (7500–7600 years). Several large extrusive domes have been built at the Bolshoy Semiachik massif. The age of the Ivanov Dome determined from correlation with the dated marker ash KRM is roughly 8500–9000 years. Korona and Ezh Domes were built about 5600 years ago; a date of 5620±50 years (GIN-5281) has been obtained for peat underlying their tephra which lies under the AV_5 marker layer dated at 5600 years (Fig. 7).

Late Pleistocene volcanoes and calderas

Isotopic-geochronological age determinations for Late Pleistocene calderas and volcanoes of the Kurile-Kamchatka region (Fig. 1A) are meager (Table 5, Fig. 11).

Late Pleistocene calderas

The large crater (caldera) within which the active Shiveluch volcano (young Shiveluch) is located seems to have formed about 30000 years ago as ashes from this caldera-forming eruption found in the bottom sediments in the Bering Sea and Litke Strait are dated at 30200±50 years.

Uzon caldera formed 39000 years ago, as shown by the date obtained on soil at the base of welded tuffs which was exposed at the shore of the Kronotskoe Lake.

Krasheninnikov caldera is roughly the same age as the Uzon caldera; its pyroclastic flow deposits directly overlie the Uzon ignimbrites.

Karymsky Lake caldera may have formed within the time interval of 28000 to 48000 years ago according to data obtained by the fission track method (Masurenkov 1980a). Maly Semiachik caldera is roughly the same age (probably 25000–30000 years ago), as its tuffs overlie the pyroclastics from the Karymsky Lake caldera.

Khangar caldera formed around 38000–40000 years ago, as the age of intercalated tephra from its caldera-forming eruptions in loess-like Upper Pleistocene deposits of the Central Kamchatka Depression ranges from 38000±1800 to 40600±700 years.

The date of 29900±900 years was obtained for a large Late Pleistocene crater (caldera) at Mount Avachinsky somma, within which its young cone is located. This age was determined on organic matter extracted from the coastal marine deposits underlying the pyroclastics (debris avalanche and directed blast deposits) at the coast of the Avachinsky Bay in Petropavlovsk, which are linked to the formation of this crater (Melekestsev et al. 1991c).

Opala caldera formed 40000 years ago based on the dates obtained above and under the tephra from that eruption in peat bogs of coastal precipices in West Kamchatka (Table 5). Earler it was shown by Melekestsev et al. (1974a) that pyroclastic deposits in the Opala caldera are interbedded among glacial deposits of stage I of the Late Pleistocene glaciation and are overlapped by moraines of stage II. Dates obtained indicate that the Opala caldera can be correctly referred to the Late

Table 5 Ages of Late Pleistocene calderas in the Kurile–Kamchatka region

Names of calderas	^{14}C ages (years)	Laboratory index	Comments	^{14}C ages (ka)
Shiveluch	30200± 500	IVAN-148	p	~30
Uzon	39600±1000	GIN-1369	bs	~39
Krasheninnikova	<39600±1000			~35–38 (?)
Karymsky Lake	–			28–48*
Maly Semiachik	–			<28–48
Khangar	38000±1800	GIN-3404	bs	38–40
	40600± 700	GIN-3401	bs	
Avachinsky crater	29900± 900	GIN-5563	bs	29–30
Opala	39400±1400	GIN-3008	p	39–40
	~41000	GIN-3009	p	
Gorely	33600± 700	GIN-5305	bs	33–34
Kuril Lake ('old')	41500± 900	GIN-6081	bs	40–41
Nemo III	24500± 740	KSM-443	bs	24–25
Mendeleev	39300± 600	GIN-124a	p	39–40
	40200± 750	GIN-124b	p	
Golovnin	38800± 800	GIN-581	p	38–39

* Dates determined by fission-track method. Other symbols as in Table 3.

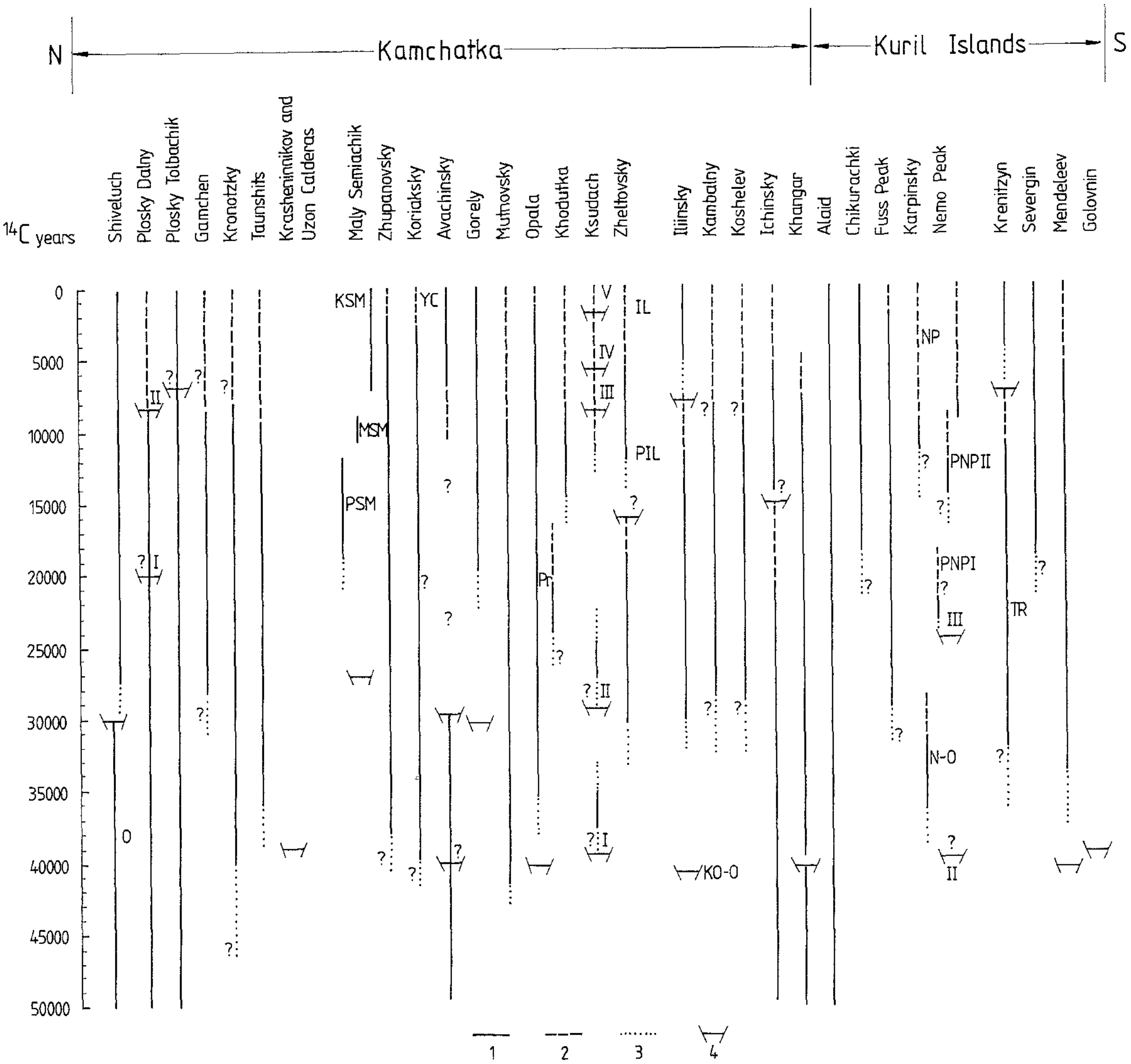

Fig. 11 Ages of active and potentially active volcanoes of the Late Pleistocene and dated Late Pleistocene calderas. **1,** Period of intense volcanic activity; **2,** period of waning volcanic activity, including fumarolic; **3,** periods of presumed early volcanic activity; and **4,** calderas. Indices: Y, young Shiveluch; O, old Shiveluch; KSM, Kaino-Semiachik; MSM, Meso-Semiachik; PSM, Paleo-Semiachik; YC, young cone of Avachinsky volcano; Pr, Priemysh; KO-O, old Kuril Lake caldera; PIL, Pre-Iliinsky; IL, Iliinsky; NP, Peak Nemo; PNPI, II, Pre-Peak Nemo I and II; N-O, old Nemo; and TR, Tao-Rusyr

Pleistocene Interstade. Gorely caldera is roughly the same age as the Opala caldera, as ignimbrites from its caldera-forming eruptions enter joints in the Opala pumice pyroclastic deposits. Dacite pumice tephra from one of the eruptions related to the formation of the Gorely caldera is underlain in Petropavlovsk by buried soils whose age is 33600±700 years.

Radiocarbon dates for Ksudach calderas KSI and KSII are lacking. They are thought to be Late Pleistocene in age because of the good preservation of caldera morphology and correlation with stage II moraines of the Late Pleistocene glaciation. The calderas already existed during the climax of glaciation (20000–25000 years ago) and served as large ice basins (Melekestsev et al. 1974a).

The Late Pleistocene ('old') Kuril Lake caldera in south Kamchatka apparently formed about 41000–42000 years ago. Ash from this caldera-forming eruption was identified and dated (Table 5) as far as the city of Magadan (about 1000 km from the vent; Melekestsev et al. 1991b).

Of three Nemo calderas on Onekotan Island, only the youngest (Nemo III) within which the presently active Nemo volcano is located was dated. The age of carbonized detritus on soils underlying the pyroclastics in the caldera is 24500±740 years.

Mendeleev and Colovnin calderas on Kunashir Island are of a similar age. Mendeleev caldera formed about 39000–40000 years ago, as shown by several accordant dates on peat underlying the pyroclastic deposits. Golovnin caldera formed about 38000 years ago, as shown by the date on peat underlying the pyroclastic deposits related to this caldera (Table 5).

Fig. 12 Late Pleistocene Kronotsky volcano. View to north-east. Photo by N. A. Smelov

Late Pleistocene volcanoes

We have noted the difficulty in determining the radiocarbon age of Late Pleistocene volcanoes due to the poor preservation of their pyroclastic deposits and an organic matter deficiency in them. Numerous questionmarks in Fig. 11 show the limitations and ambiguity of our present state of study. Nevertheless, this figure shows the ages of recently active volcanoes which began to form in Late Pleistocene times, which we have compiled by combining geological–geomorphological evidence with the meager radiocarbon dates.

Maly Semiachik, Khangar, Opala (Fig. 8), Gorely and Peak Nemo are obviously younger than the dated Late Pleistocene calderas enclosing them. For some volcanoes located in the proximity of calderas, their ages were measured by correlation of their volcanics with the dated caldera pyroclastic deposits. Thus, for example, estimates obtained by using this correlation for the age of Taunshits volcano, whose lavas overlie the Uzon caldera ignimbrites, indicate an age <39 000 years.

We assume that many recently active volcanoes that originated in Late Pleistocene times already existed as large volcanic edifices at the beginning stage II of the Late Pleistocene glaciation, as they were centers of glaciation during the main glacial pulse of stage II and supplied fresh material forming large moraines which surround the volcanic cones and cover large areas at their feet. At the same time they could not originate during stage I of the glaciation, as typical sculpturesque glacial forms such as cirques and troughs which formed at more ancient edifices are lacking on them (Melekestsev et al. 1971). We therefore assume that these volcanoes began to form between the two stages of the glaciation, roughly 40 000–50 000 years ago. These are Kronotsky (Fig. 12), Taunshits, Zhupanovsky, Koriaksky, Avachinsky, Kozelsky, Mutnovsky, Opala (Fig. 8), Khodutkinsky and some others (Fig. 10).

Summary

We have provided information on the age of most large Late Pleistocene and Holocene volcanic landforms, calderas and stratovolcanoes in Kamchatka. Fifteen 'Krakatoa-type' calderas formed here in the Late Pleistocene (Fig. 1A). The ages of 12 of them have been estimated. There is no data on three Late Pleistocene calderas: Ichinsky, Zheltovsky and Prizrak calderas. All calderas, except for Ichinsky and Khangar located in the Sredinny Ridge, were emplaced within the Eastern volcanic belt.

Six 'Krakatoa-type' calderas that emerged in Kamchatka during the Holocene are located within the Eastern volcanic belt and spatially associated with some of the Late Pleistocene calderas. The Holocene Kuril Lake and Iliinsky calderas are nested within the Late Pleistocene 'Old' Kuril Lake caldera. The Holocene Ksudach calderas (III, IV and V) are nested in Late Pleistocene calderas I and II. The Holocene Karymsky caldera is located nearby the Late Pleistocene Karymsky Lake caldera. No Holocene 'Krakatoa-type' calderas occur in the Kliuchevskoi volcano group, but two of three Holocene 'Hawaiian-type' calderas are located within it. Five of six Holocene 'Krakatoa-type' calderas in Kamchatka formed within the southern part of the Eastern volcanic belt and two more calderas formed in the Kuril Islands. Five large calderas are nested within the Ksudach massif, three of which formed in Holocene time. The Holocene calderas are much smaller in size and volume of ejecta than Late Pleistocene calderas.

Most Late Pleistocene calderas formed roughly 30 000–40 000 years ago (Table 5). All but one Holocene caldera in the Kuril–Kamchatka region formed in the first part of the Holocene between 9500 and 6000 years BP (Fig. 5).

Most of the Late Pleistocene stratovolcanoes in Kamchatka formed within the Eastern volcanic belt, except for two volcanoes that formed in the Sredinny Ridge. Stratovolcanoes have been formed throughout the entire Holocene period, but only within the Eastern volcanic belt. Monogenetic forms initiated in the Holocene both in the Eastern volcanic belt and in the Sredinny Ridge.

Although this chronicle contains some gaps, we can define periods of synchronous upsurge of volcanic activity in the Kuril–Kamchatka region in the Holocene. One of them is between 7800 and 7500 years ago when a powerful paroxysm of acid explosive volcanism took place. As a result, the calderas of Karymsky, Kuril Lake, Íliinsky and Tao-Rusyr were formed almost synchronously (Fig. 5), but in consecutive order from north to south. Simultaneously, large explosive eruptions of Kizimen (which produced the marker ash KZ), Taunshits and Shiveluch took place, and Dikiy Greben volcano began to form. After this paroxysm, the Kaino-Semiachik basaltic volcano started to form. Considering the estimated tephra volumes and the zonal atmospheric circulation, we suppose that the large explosive eruptions of this period are responsible for some of significant acidity peaks in Greenland ice cores (Zielinski et al. 1994) and may have contributed to climatic cooling.

One more period of synchronous upsurge of activity was 1800–1300 years ago when caldera V at Ksudach and Baraniy Amfiteatr crater at Opala volcano formed. Several powerful explosive eruptions of Shiveluch volcano also took place (one of them produced the marker tephra SH_3). In addition, several stratovolcanoes were initiated (Mid-North cone at Krasheninnikov, Savich cone at Kikhpinych and Shtyubel cone at Ksudach) and a huge extrusive dome (Mt Nepriyatnaya) was emplaced at Dikiy Greben volcano (Figs 5 and 7). This is also the time when magnesian basalts started to erupt in the Tolbachik regional zone (about 1600 years BP). Afterwards, during the last 1300 years, only one stratovolcano, Neo-Bezymianny, started to form.

According to our data, the duration of building large stratovolcanoes is estimated to be several thousand years. Thus small stratovolcanoes such as both cones of Kikhpinych, Shtyubel in the Ksudach massif and the Mid-North cone of Krasheninnikov formed their edifices in the main in only a few hundred years. It took a few thousand years for the following large stratovolcanoes to build their cones in the main: Young cone of Avachinsky volcano (3500 years), Bezymianny (3700 years) (Braitseva et al. 1991), North cone of Krasheninnikov (3100 years) (Ponomareva 1990), Karymsky (2800 years) (Braitseva and Melekestsev 1991) and Kaino-Semiachik (5200 years) (Braitseva et al. 1980). The cone of Kliuchevskoi grew for over 3000 years before its first flank eruptions started to occur roughly 3000–3500 years ago.

Volcanoes which started to form in the Holocene or at the very end of the Late Pleistocene have remained very active until the present time. A sustained supply of the volcanic material reduces the erosion–denudation effects to zero and is the reason for the good preservation of the initial volcanic edifice morphology (Figs 6 and 10). Most of the volcanoes that started to form in the Late Pleistocene exhibited waning activity in the Holocene. Minor supplies of volcanic material allowed denudation to promptly change the appearance of the volcano; it became dissected by deep gullies and by dry river valleys (Figs 8 and 12) and entered the stage of starting edifice destruction. Consequently, the preservation of the initial morphology of volcanic cones is mainly dependent on the intensity of volcanic activity, which is closely linked to the age of volcanoes (Melekestsev 1973).

Data obtained in Kamchatka and the Kuril Islands suggest that recently active volcanic cones of this area are geologically very young; their maximum age is roughly 50000 years; the most active volcanoes started to form only a few thousand years ago. These data are in good agreement with the results of radioisotopic age determinations for active volcanoes in other volcanic regions with different geotectonic environments (Thorarinsson 1967; Crandell and Mullineaux 1978; Aramaki et al. 1981; Ono et al. 1981; Tsuya et al. 1981; Chester et al. 1985; Easton 1987; Rose 1987).

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