

RADIOCARBON DATING OF LARGE HOLOCENE VOLCANIC EVENTS WITHIN SOUTH KAMCHATKA (RUSSIAN FAR EAST)

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ABSTRACT. Radiocarbon dating is widely used when studying recent volcanic activity in the Kamchatka Peninsula due to the abundance of organic matter that is associated with the volcanic deposits. Here, we present the results of ^{14}C dating of major volcanic events within the active South Kamchatka volcanic zone. South Kamchatka includes 8 recently active volcanic centers (stratovolcanoes, calderas, and large craters) that have been erupting during the Holocene. Their tephras represent useful markers for both the southern part of the peninsula and the Northern Kurile Islands. Since these marker tephra layers facilitate stratigraphic and tephrochronological studies in this area, it was important to determine their ages. We have obtained 73 new individual ^{14}C dates on paleosol, peat, charcoal, and wood associated with the marker tephra layers, then complemented these data with 37 earlier published dates and analyzed the resulting data set. We selected the reliable dates and then obtained average ^{14}C ages of marker tephra layers. The details of these procedures, as well as brief descriptions of South Kamchatka Holocene eruptions and their tephra beds, are presented in the paper.

INTRODUCTION

Radiocarbon dating is widely used when studying recent volcanic activity in the Kamchatka Peninsula, northwestern Pacific region (Sulerzhitsky 1971; Braitseva et al. 1993, 1995, 1997; Zaretskaia et al. 2001a,b). Here, it has proved to work better for the late Pleistocene-Holocene deposits than other methods of isotope dating (e.g. $^{40}Ar/^{39}Ar$, K/Ar, U/Th) due to the abundance and high productivity of organic matter associated with the volcanic deposits of this age, and the lack of K in the young volcanic rocks. In this paper, we describe ^{14}C dating of major Holocene volcanic events within the active South Kamchatka volcanic zone. We provide 73 new and 37 earlier published dates on the organic matter associated with the Holocene tephra layers (Table 1); discuss the validity and significance of the dates, which depend on the characteristics of the dated material; and finally, present a list of dated key-marker tephra layers in South Kamchatka. These tephra layers document the largest explosive eruptions in this region.

South Kamchatka (Figures 1 and 2) hosts a number of volcanic centers that have produced large explosive eruptions during the Holocene. These are, from north to south: the Chasha Crater, the Baranii Amphitheater Crater at the foot of Opala Volcano, and Khodutkinsky Crater; the Ksudach caldera massif with a young stratovolcano, Stübel Cone, inside; the Zheltovsky and Iliinsky volcanoes; the large Kurile Lake caldera; and the Dikii Greben' and Kambalny volcanoes. The largest Holocene explosive eruption of the region (coded KO) has resulted in the formation of the Kurile Lake caldera. The eruption took place ~7.6 kyr BP (Zaretskaia et al. 2001b). It has a conservatively estimated tephra volume of 140–170 km^3, making it the largest Holocene eruption in the Kurile–Kamchatka volcanic arc and ranking it among Earth's largest Holocene explosive eruptions (Ponomareva et al. 2004). The KO tephra was dispersed over an area of >3 million km^2, mostly in a northwest direction (Figure 1). It is a valuable stratigraphic marker for southern Kamchatka, the Sea of Okhotsk, and a large part of the Asian mainland, where it has been identified as a 6- to 0.1-cm-thick layer in terrestrial and lake sediments, 1000–1700 km from the source (Anderson et al. 1998; Gorbarenko et al. 2002). The KO ignimbrite is ~140 m thick near the lake and extends to the Sea of Okhotsk and the Pacific Ocean on either side of the peninsula. The KO tephra is an important benchmark for the Holocene stratigraphy of South Kamchatka.

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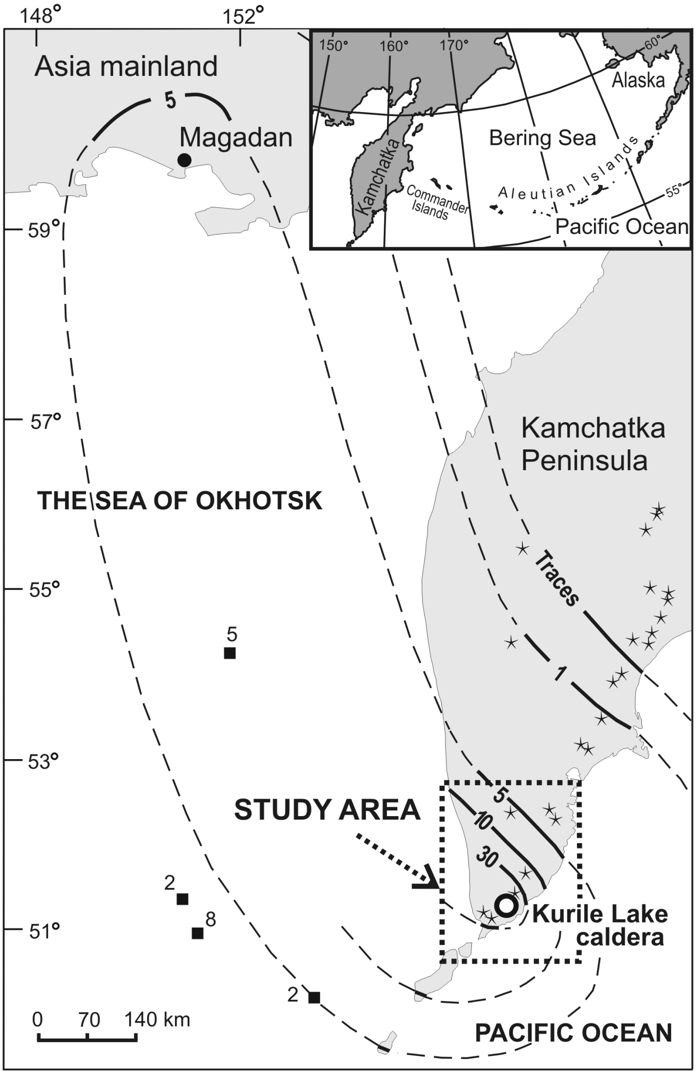

KO tephra dispersal

– 1 —	Isopachs based on ground measurements (thickness in cm)	2 ■	Sea cores and thickness of KO ash in cm
- - - - -	Presumed isopachs	⋆	Holocene volcanoes

Figure 1 Location of the study area and dispersal of the largest South Kamchatka tephra, associated with the Kurile Lake caldera-forming eruption. The inset shows the location of Kamchatka within the northern Pacific region.

Three other tephras (KS_1 and KS_2 from Ksudach caldera and OP from Baranii Amphitheater Crater at the foot of Opala Volcano) yielded volumes of 9–19 km^3 and also covered large territories (Melekestsev et al. 1996b; Braitseva et al. 1997; Volynets et al. 1999). These tephra layers were dated earlier based on numerous individual ^{14}C dates (Braitseva et al. 1995, 1997).

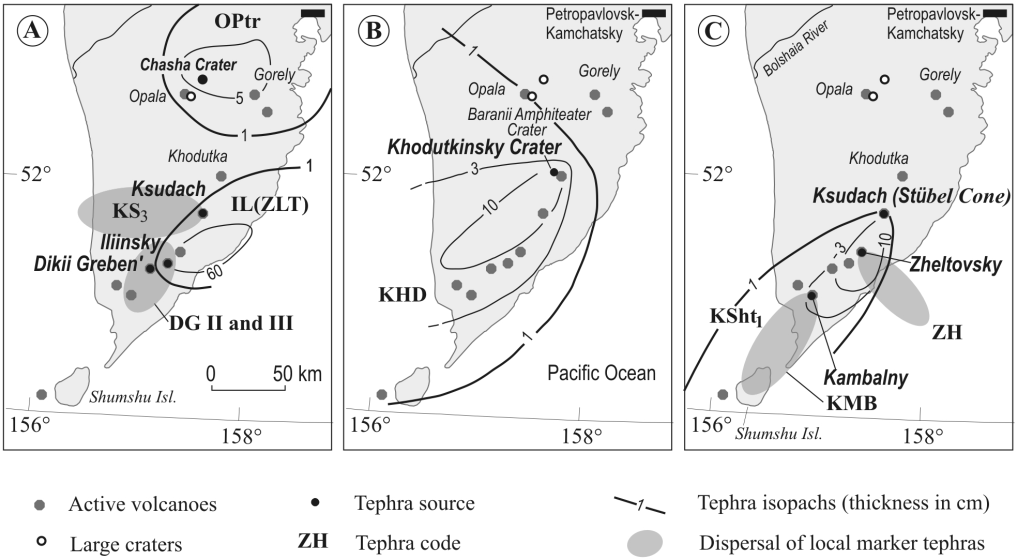

Figure 2 Dispersal of the key-marker tephra layers in South Kamchatka. For codes of tephra layers, see the text and Table 2. OP_{tr} isopachs are modified from Dirksen et al. (2002); other isopachs and areas of tephra dispersal are based on the authors' field data.

Ten more tephra layers with smaller volumes also play an important role in the Holocene stratigraphy in the southern part of the peninsula and Northern Kurile Islands and record large explosive eruptions of local volcanoes (Table 2). Five of those (KS_3, IL [ZLT], OP_{tr}, KHD, and KSt_1) have been dated and briefly described earlier (Braitseva et al. 1997). We evaluate published dates, provide new ones, and refine the ages of these volcanic events. In addition, we have identified and dated 5 more marker tephra layers (DG II, DG III, KMB_{phr}, ZH, and ZH_1).

METHODS

Radiocarbon Dating: Field Sampling, Pretreatment, and Date Selection

Tephra layers are widespread in the Kamchatka Peninsula, which hosts more than 30 active volcanoes. Holocene tephra layers separated by soils, sandy loams, or peats form the soil-pyroclastic cover that blankets most of Kamchatka. This cover is a few tens of centimeters thick in areas far from the active volcanoes and increases up to several meters at their source. The cover provides a continuous record of the explosive eruptions during the Holocene, while earlier tephra layers in Kamchatka were mostly destroyed during Late Pleistocene glaciation and occur as isolated beds.

We performed the ^{14}C dating of various organic matter (paleosols, sandy loams, peat, charcoal, and wood) associated with the marker tephra layers. The samples were collected in different depositional environments in South Kamchatka, at different distances from the eruptive sources.

In South Kamchatka, paleosols and organic-poor sandy loams, buried by tephra layers, are 1–15 cm thick and have no developed soil profile. They are composed of redeposited ash variably enriched in organic matter. For ^{14}C dating, we collected bulk samples of paleosols and sandy loams above and beneath tephra layers. Normally, we tried to collect thin (~1 cm) layers of organic-repleted soils, but sometimes we had to collect thick (3–5 cm) layers of sandy loams to obtain a sufficient quantity of material for dating.

The standard acid-alkali-acid (AAA) pretreatment procedure was used to measure the age of the alkali-soluble fraction of the soils. In an attempt to add precision to the dating of an eruption (particularly while dating thick soil layers), we generally retrieved and dated 2 consecutive alkali extractions (cold and then hot) from 1 bulk sample (Braitseva et al. 1993; Zaretskaia et al. 2001a); thus, we obtained 2 dates on 1 soil sample (marked with $_{I}$ and $_{II}$ after the laboratory number in Table 1). Ages obtained by previous investigators (marked with * in Table 1) were mostly obtained on material from a single hot alkaline extraction. In estimating the age of a tephra layer, we normally selected the younger date from the underlying soil layer and the older date from the overlying soil layer.

Some dates on a long-lived paleosol, even on its upper part, may yield any ages within the limits of this paleosol formation interval and thus be significantly older than the age of the overlying tephra (e.g. Ponomareva et al. 2001). For this reason, dates were obtained on successive alkaline extractions from several samples in order to determine reproducibility.

Peat bogs, enclosing volcanic tephra layers and lahar (volcanic mudflow) deposits, are widespread in Kamchatka. Peat seems useful for dating explosive eruptions because even the thinnest ("one-grain-thick") tephra layers are clearly recoverable from the peat. Peat bogs are continuously growing systems with organic matter accumulating during the Holocene. In most cases, the deposition of a thin layer of tephra does not interrupt peat accumulation (Hotes et al. 2004), so by dating material from above and beneath peat layers, we can constrain more effectively the ages of marker tephras.

We collected bulk peat samples from above and beneath tephra layers. Once again, the A-A_{cold}-A_{hot}-A procedure was utilized and 2 subsamples (derived from the cold and hot alkaline extractions) were dated from each bulk sample (i.e. a procedure similar to the paleosols pretreatment). In cases where plant remnants were well preserved, we recovered both the cold extraction and the alkali-insoluble fraction. For small samples, we applied a single hot alkaline extraction and dated 1 sample. Most of the previously published dates were measured on material treated using a single hot alkaline extraction.

In Kamchatka, dates of bulk peat may sometimes result in younger ages than expected due to the contamination of the peat layer with young roots coming from the upper layers of the bog (Zaretskaia et al. 2001a). We therefore analyzed the plant composition of each peat sample and then studied all determined species in a herbarium (Institute of Botany, Russian Academy of Sciences, St. Petersburg) to understand the reasons for this. We found several sedge species with very long roots penetrating through tephra and peat layers into older stratigraphic levels. These are *Carex cryptocarpa* C.A. Mey, *C. vesicata* Meinsh., *C. monile* Tuckerm., and *C. middendorffii* Fr. Schmidt. The length of the sedge roots can exceed 1 m (Alexeev 1996), and, according to our field observations, they can penetrate through <7-cm-thick layers of fine-grained and <2-cm-thick layers of coarse ash. Individual peat samples may contain up to 90% of these long-root sedges. When analyzing the plant composition of a bulk peat sample, one cannot determine whether fragments of these long-root sedges belong to this particular peat horizon or have penetrated from the younger layers. Thus, the presence of these sedges in a peat sample is a good indicator that the sample may produce an age younger than expected based on its stratigraphic position. We concluded that sample contamination by younger roots might take place in these cases (Zaretskaia and Uspenskaia 2001; Zaretskaia et al. 2001a). Other Cyperaceous plants (such as *Carex lasiocarpa*, *C. pauciflora* Liqhtf., and other sedges), rootless mosses (*Sphagnum* or *Bryales*), or other grasses (*Calamagrostis langsdorffii*, *Equisetum fluviatile* L., etc.) generally do not influence the ^{14}C age of a bulk peat sample. With this in mind, we have determined plant composition for each of the peat samples dated in this study (Table 1).

Table 1 ^{14}C dates for key-marker tephra layers in South Kamchatka, Russian Far East.[a]

Source-volcano and eruption code	Lab code and number	Sample type	Sampling site (location)	Dominant plant species in peat	^{14}C age
Ksudach, KS_3	GIN-5685_I*	Underlying soil	Ksudach caldera	—	6130 ± 40
	GIN-5685_{II}*				6260 ± 60
	IVAN-802*	Overlying soil	Ksudach caldera	—	6130 ± 70
	GIN-9683_I	Underlying soil, 3 cm thickness	Golygina River, west of Ksudach	—	**6400 ± 180**
	GIN-9683_{II}				6700 ± 40
	GIN-9678_I	Overlying peat	Golygina River, west of Ksudach	*Carex cryptocarpa* C.A. Mey – 70%	6190 ± 40
	GIN-9678_{II}			*C. pauciflora* Liqhtf. – 20% Bush bark – 10%	**6300 ± 90**
	GIN-9679_I	Underlying peat	Golygina River, west of Ksudach	*Equisetum fluviatile* L. – 60%	**6380 ± 40**
	GIN-9679_{II}			*Carex* sp. – 40%	6400 ± 50
Iliinsky, IL (ZLT)	GIN-4929_0*	Underlying soil, 5 cm thickness	Iliinskaia River, south slope of Zheltovsky	—	5350 ± 120
	GIN-4929_I*				5370 ± 70
	GIN-4929_{II}*				5840 ± 150
	GIN-4931_Σ*	Charcoal inside the tephra	Northern shore of Kurile Lake	—	5020 ± 50
	IVAN-829_I*	Underlying soil, 1 cm thickness	Northern slope of Zheltovsky	—	5500 ± 120
	IVAN-830_I*	Underlying soil, 1 cm thickness	Northern slope of Zheltovsky	—	5520 ± 120
	GIN-8111$*_{outer}$	Charcoal inside the tephra	Northern shore of Kurile Lake	—	**4890 ± 40**
	GIN-8111$*_{inner}$				**4800 ± 40**
	GIN-8112_Σ*	Underlying soil	Northern shore of Kurile Lake	—	4570 ± 70
	GIN-8774_I	Underlying soil	Northern shore of Kurile Lake	—	**4900 ± 70**
	GIN-8774_{II}				4850 ± 120
	GIN-8775_Σ	Charcoal inside the tephra	Northern shore of Kurile Lake	—	5500 ± 40
	GIN-8775				**4900 ± 50**
	GIN-11582_I	Underlying peat	Northern part of Vestnik Bay	*C. cryptocarpa* – 90%	5040 ± 40
	GIN-11582_{II}			*Equisetum fluviatile* – 10%	**4870 ± 40**
Chasha Crater, OP_{tr}	IVAN-472_Σ*	Overlying peat	Mutnovsky Volcano	Undetermined	**4620 ± 100**
	IVAN-675_I	Underlying peat	Opala caldera	Undetermined	4880 ± 50
	IVAN-675_{II}*				**4660 ± 200**
	GIN-9669_I*	Underlying soil	Tolmacheva River	—	4950 ± 50
	GIN-9669_{II}*				5030 ± 120
	GIN-9692_I*	Overlying peat	Opala caldera	*C. middendorffii* – 60%	**4630 ± 40**
	GIN-9692_{II}*			*Eriophorum* sp. – 25%	4360 ± 160
	GIN-9693_I*	Underlying peat	Opala caldera	*Sphagnum fuscum* – 45%	4710 ± 40
	GIN-9693_{II}*			*Carex* sp. – 40%	**4510 ± 80**

Table 1 ^{14}C dates for key-marker tephra layers in South Kamchatka, Russian Far East.[a] *(Continued)*

Source-volcano and eruption code	Lab code and number	Sample type	Sampling site (location)	Dominant plant species in peat	^{14}C age
Dikii Greben', DG II	GIN-8114$_I$*	Overlying soil	Northern shore of Kurile Lake	—	3420 ± 100
	GIN-8114$_{II}$*				4230 ± 160
	GIN-8765$_I$	Overlying soil	Northern shore of Kurile Lake	—	4090 ± 50
	GIN-8765$_{II}$				4250 ± 150
	GIN-9150$_I$	Underlying sandy loam	Dikii Greben' Volcano	—	4500 ± 220
	GIN-9182$_I$	Overlying peat	Khakytsyn River	*Eriophorum* sp. – 30%	4360 ± 80
	GIN-9182$_{II}$			*Calamagrostis* sp. – 15%	**4480 ± 80**
				Carex sp. – 30%	
				Undetermined – 20%	
	GIN-9183$_I$	Underlying peat	Khakytsyn River	*Drepanocladus exannulatus* +	**4380 ± 70**
	GIN-9183$_{II}$			*D. aduncus* Warnst. – 35%	4550 ± 60
				Sphagnum palustre – 20%	
				Carex sp. – 30%	
	GIN-8752$_I$	Overlying peat	Khakytsyn River	*C. rhynchophysa* C.A. Mey – 90%	4070 ± 40
	GIN-8752$_{II}$			*C. vesicata* Meinsh. – 10%	4110 ± 40
	GIN-8753$_I$	Underlying peat	Khakytsyn River	*C. rhynchophysa* – 95%	4310 ± 40
				C. vesicata – 5%	
	GIN-9215$_I$	Overlying peat	Koshelev-Kambalny saddle	*C. cryptocarpa* – 55%	4140 ± 80
	GIN-9215$_{II}$			*Carex* sp. – 45%	4240 ± 110
	GIN-9216$_I$	Underlying peat	Koshelev-Kambalny saddle	*C. rhynchophysa* +	4620 ± 110
	GIN-9216$_{II}$			*Carex monile* Tuckerm. – 45%	4740 ± 110
				Carex sp. – 40%	
Khodutkinsky Crater, KHD	GIN-2970$_{II}$*	Underlying soil, 20 cm thickness	NW slope of Ksudach	—	**2490 ± 120**
	GIN-2970$_I$*				3120 ± 170
	GIN-2291$_I$	Underlying peat	Khodutka Volcano	Undetermined	2990 ± 50
	GIN-2291$_{II}$*				2850 ± 120
	GIN-4934$_\Sigma$*	Underlying peat	Zheltovsky Volcano	Undetermined	2800 ± 40
	GIN-9205$_I$	Underlying peat	Koshelev-Kambalny saddle	*C. cryptocarpa* – 90%	2130 ± 140
	GIN-9205			*Carex* sp. – 10%	2060 ± 150
	GIN-8751$_I$	Underlying peat	Khakytsyn River	*C. vesicata* – 95%	2560 ± 100
	GIN-8751$_{II}$			*Equisetum* – 5%	**2460 ± 60**
	GIN-8761$_I$	Underlying peat	Khakytsyn River	*Sphagnum fimbriatum* Wils. – 80%	**2530 ± 90**
	GIN-8761$_{II}$			*Eriophorum* sp. – 10%	2800 ± 100
	GIN-9171$_I$	Overlying peat	Khakytsyn River	*C. cryptocarpa* – 35%	2490 ± 100
	GIN-9171			*Eriophorum* sp. – 50%	**2530 ± 90**

Table 1 ^{14}C dates for key-marker tephra layers in South Kamchatka, Russian Far East.[a] *(Continued)*

Source-volcano and eruption code	Lab code and number	Sample type	Sampling site (location)	Dominant plant species in peat	^{14}C age
	GIN-9172$_{I}$	Underlying peat	Khakytsyn River	*Sphagnum fimbriatum* – 80%	**2570 ± 70**
	GIN-9172			*Eriophorum* sp. – 10%	2630 ± 60
	GIN-9674$_{I}$	Underlying peat	Golygina River	*C. cryptocarpa* – 75%	2770 ± 40
	GIN-9674$_{II}$			*Equisetum fluviatile* – 10%	**2500 ± 80**
	GIN-9687$_{I}$	Underlying peat	Opala caldera	*Carex* sp. – 30%	2340 ± 40
	GIN-9687$_{II}$			*Calamagrostis* sp. – 15%	2470 ± 30
				Undetermined – 40%	
Dikii Greben', DG III	GIN-8117*	Small wood pieces inside the tephra layer	Dikii Greben' Volcano	—	**1620 ± 40**
	GIN-8118*	Twigs inside the tephra layer	Dikii Greben' Volcano	—	**1600 ± 40**
	GIN-8120$_{I}$*	Underlying sandy loam, 5 cm thickness	Dikii Greben' Volcano	—	**1600 ± 30**
	GIN-8120$_{II}$*				1620 ± 40
	GIN-8122$_{I}$*	Underlying sandy loam, 4 cm thickness	Ozernaia River	—	1860 ± 120
	GIN-8122$_{II}$*				1930 ± 60
	GIN-9154	Charred branches inside the pyroclastic surge deposits	Dikii Greben' Volcano	—	**1650 ± 80**
	GIN-9151$_{I}$	Underlying soil, 5 cm thickness	Dikii Greben' Volcano	—	1860 ± 70
	GIN-9151$_{II}$				1740 ± 60
	GIN-8750$_{I}$	Overlying peat	Khakytsyn River	*C. vesicata* – 95%	1540 ± 40
	GIN-8750$_{II}$			*Equisetum* sp. – 5%	**1630 ± 40**
	GIN-9169$_{I}$	Overlying peat	Khakytsyn River	*C. cryptocarpa* – 50%	1550 ± 110
				Sphagnum subsecundum Nees – 20%	840 ± 100
				Eriophorum sp. – 15%	
Ksudach (Stübel Cone), KSht$_{1}$	GIN-4926$_{I}$*	Underlying buried soil	Southern foot of Zheltovsky	—	1090 ± 100
	GIN-4926$_{II}$				1180 ± 80
	GIN-4933$_{\Sigma}$*	Underlying peat	South of Ksudach	Undetermined	1110 ± 40
	GIN-4936$_{\Sigma}$*	Underlying peat	Eastern shore of Kurile Lake	Undetermined	1010 ± 60
	GIN-8747$_{I}$	Overlying peat	Khakytsyn River	*C. vesicata* – 95%	640 ± 100
				Carex sp. – 5%	
	GIN-8748$_{I}$	Underlying peat	Khakytsyn River	*C. vesicata* – 95%	860 ± 100
	GIN-8748$_{II}$			*Carex* sp. – 5%	650 ± 50

Table 1 ^{14}C dates for key-marker tephra layers in South Kamchatka, Russian Far East.[a] *(Continued)*

Source-volcano and eruption code	Lab code and number	Sample type	Sampling site (location)	Dominant plant species in peat	^{14}C age
	GIN-9167$_I$	Overlying peat	Khakytsyn River	*C. lasiocarpa* – 50%	880 ± 40
	GIN-9167			*C. cryptocarpa* – 30%	870 ± 40
				Eriophorum brachyantherum Trautv. et C.A. Mey – 20%	
	GIN-9168$_I$	Underlying peat	Khakytsyn River	*C. cryptocarpa* – 40%	840 ± 60
	GIN-9168			*Carex* sp. – 30%	**970 ± 60**
				Sphagnum subsecundum – 15%	
	GIN-9233$_I$	Overlying peat	Southern slope of Kambalny Volcano	*Sphagnum teres* +	**990 ± 70**
	GIN-9233			*S. fimbriatum* – 95%	800 ± 50
				Carex sp. – 5%	
	GIN-9234$_I$	Underlying peat	Southern slope of Kambalny Volcano	*Sphagnum teres* +	1020 ± 90
	GIN-9234			*S. fimbriatum* – 60%	**970 ± 40**
				Bryales – 30%	
Kambalny, KMB_{phr}	GIN-9232$_I$	Underlying peat	Southern slope of Kambalny Volcano	*Sphagnum teres* Schimp. +	780 ± 60
	GIN-9232$_{II}$			*Sphagnum fimbriatum* – 80%	**680 ± 120**
				Carex sp. – 10%	
	GIN-9231	Overlying peat	Southern slope of Kambalny Volcano	*C. pauciflora* – 50%	580 ± 90
				C. cryptocarpa – 40%	
	GIN-10369$_I$	Overlying peat	Shumshu Island	Undetermined	600 ± 60
	GIN-10370$_I$	Underlying peat	Shumshu Island	Undetermined	720 ± 40
	GIN-10370$_{II}$				**700 ± 60**
Zheltovsky, ZH_1	GIN-4923$_I$	Sandy loam	South slope of Zheltovsky	—	670 ± 40
	GIN-4923$_{II}$				810 ± 40
	GIN-6074/831	Sandy loam	Northern slope of Zheltovsky	—	**560 ± 30**
	GIN-4925$_I$	Sandy loam	South slope of Zheltovsky	—	**550 ± 50**
	GIN-4925$_{II}$				550 ± 50
	GIN-8782	Sandy loam	Iliinskaia River	—	**460 ± 110**
	GIN-11578$_I$	Underlying soil	Vestnik Bay	—	**420 ± 30**
	GIN-11578$_{II}$				580 ± 50
Zheltovsky, ZH	GIN-4924$_I$	Underlying soil	Iliinskaia River	—	180 ± 40

[a]Reliable dates are marked in bold. Earlier published dates (Braitseva et al. 1997; Ponomareva et al. 2001; Dirksen et al. 2002) are marked with *. GIN-NNN$_I$ and GIN-NNN$_{II}$ define dates obtained on cold and hot alkaline extractions, respectively; GIN-NNNK defines dates obtained on the alkali-insoluble peat fraction; GIN-NNN$_\Sigma$ means that the hot and cold alkaline extractions were combined and 1 date received.

Charcoal and wood are quite rare within the marker tephra horizons of South Kamchatka. Generally, we found only small charred and uncharred twigs buried by ash. We performed a standard AAA pretreatment procedure for both materials. Generally, all the dates appear accurate. There is no fear of inbuilt age due to the short time span of their growth.

In analyzing the whole set of ^{14}C dates, we applied the following criteria:

1. We performed a validity screening, analyzing sample origin, composition, and type of organic matter in each dated sample, excluding "outlier" dates (e.g. dates on redeposited wood, those obtained on peat samples contaminated by long-root sedges from the upper stratigraphic horizons, dates obtained on a single hot alkaline extraction from a thick soil/peat horizon, etc.). All these cases are discussed in the text.
2. After identifying reliable dates, we combined them using the R_Combine function in OxCal v 3.10 (Bronk Ramsey 1995, 2001) and the IntCal04 calibration curve (Reimer et al. 2004). This gave us the mean ^{14}C age for each marker tephra horizon.
3. We publish all ^{14}C determinations to enable other researchers to evaluate our procedure. Calibrated (calendar) ages are not provided since these vary and are frequently updated. Using different programs and approaches yields slightly different calendar ages. We cannot compare directly the ages of marker tephras to any calendar events (e.g. ice cores, dendrochronology, archaeological records, etc.) since the latter are not available for this region.

DATED ERUPTIONS: RESULTS AND DISCUSSION

We discuss the dated eruptions in chronological order, both in the text and in Tables 1 and 2.

Ksudach Volcano is a shield-like polygenetic edifice composed of lavas and tephra of multiple eruptive centers of various age and morphology. It comprises nested calderas formed during 5 collapse events. A small stratovolcano named Stübel Cone is located in the most recent caldera. The most prominent marker tephra layers from Ksudach are KS_1, KS_2, and KS_3, related to caldera-forming eruptions, and KSt_1 from Stübel Cone (Table 2). Caldera IV formed as a result of 2 large eruptions, KS_3 and KS_2, closely spaced in time, which produced explosive breccias, pyroclastic flows, and ash falls with a total volume of tephra of about 10–11 km^3 (Melekestsev et al. 1996a). The KS_2 ash-fall axis was directed to the north, and the KS_3 axis to the west (Figure 2A).

The age of this event was earlier roughly estimated as 6300 BP (Volynets et al. 1999). In peat sections (new data), the KS_3 tephra layer is separated from KS_2, dated to ~6000 BP (Braitseva et al. 1997), by 4–5 cm of peat. This is why the date 6130 ± 40 BP (GIN-5685$_I$) under the KS_3 tephra is probably too young. This may be explained by the fact that this date was obtained inside the Ksudach calderas, where stratigraphy is complicated. The dates from above and below the peat layers from the individual peat section (6300 ± 90 and 6380 ± 40 BP) were considered to be reliable since the *Carex cryptocarpa* from the overlying peat had not penetrated through the ash layer. The underlying peat consists mostly of horsepine, and the peat layer overlying sample GIN-9678 consists of *Sphagnum* mosses. A date of 6400 ± 180 BP was obtained on the organic-rich soil sample underlying the KS_3 tephra and is considered reliable. An average ^{14}C age of KS_3 was calculated at 6386 ± 36 BP.

The IL tephra was earlier attributed to the Zheltovsky Volcano and thus coded ZLT (Melekestsev et al. 1996b). Further field investigations have enabled us to instead attribute it to the Iliinsky Volcano and thus recode it IL. Iliinsky Volcano is located in the northeastern part of the Kurile Lake caldera. It started to form soon after the formation of the caldera (Ponomareva et al. 2004) and it is an active center, with the last historic eruption taking place in 1901. This formed a large crater on its eastern slope. The thick cover of Iliinsky pyroclastic deposits is widespread over the Kurile Lake area. The

Table 2 Holocene prehistoric key-marker tephra layers at South Kamchatka.[a]

Source-volcano	Code	Average age, ^{14}C yr BP	Description	Composition	Characteristic geochemical and mineralogical features
Zheltovsky	ZH	Historical	Dense black lapilli rich in allivalite and eucrite inclusions	B	Low K_2O content
Zheltovsky	ZH_1	500	Pinkish coarse tephra	A	Low K_2O content
Kambalny	KMB_{phr}	700	Coarse tephra of a phreatic eruption	Mixed	—
Ksudach (Stübel Cone)	$KSht_1$	980	Two-layer structure: lower subunit is composed of black basaltic andesite scoria whereas the upper sub-unit is yellow dacitic pumiceous coarse ash	D BA	Low K_2O content, absence of Hb
Dikii Greben'	DG III	1610	Gray coarse to fine ash	RD	Medium K_2O content, presence of Hb
Khodutkinsky Crater	KHD	2510	White or light-pale fine ash in places with admixture of light-gray coarse ash at the bottom	R	Medium K_2O content, presence of Hb
Dikii Greben'	DG II	4420	Bright-yellow fine ash with admixture of coarse grains	RD	Medium K_2O content, presence of Hb
Chasha Crater	OP_{tr}	4610	Light yellow fine to coarse tephra	R	High K_2O content, presence of Bi
Iliinsky	IL (ZLT)	4860	Yellow or pinkish pumice bombs and lapilli	A	Low-medium K_2O content, presence of Hb
Ksudach	KS_3	6390	Yellow and gray pumiceous coarse ash, often iron-stained	A	Low K_2O content, absence of Hb
Kurile Lake caldera	KO	7610	Voluminous fall and ignimbrite in the Kurile Lake region; pale fine and coarse ash at Ksudach and farther north; pale fine and coarse ash at the Northern Kurile Islands	Ashfall - R Ignimbrite - R - BA	Low-medium K_2O content, presence of Hb

[a]Tephra layers are listed in chronological order. In column 3, the ages are the weighted average ^{14}C ages determined using OxCal v 3.10 and rounded to the nearest 10 yr. The age of the KO tephra is from Zaretskaia et al. (2001b); other ages are either obtained or refined in the present study. In column 5, the average bulk composition of the ash is given: B, A, BA, D, RD, R - corresponding to basalt, andesite, basaltic andesite, dacite, rhyodacite, rhyolite. In column 6, Hb is hornblende and Bi is biotite. Data on the composition of marker tephras from Ksudach Volcano are from Volynets et al. (1999); Dikii Greben', Bindeman and Bailey (1994); Khodutkinsky Crater and Iliinsky, Braitseva et al. (1997); and Kurile Lake caldera, Ponomareva et al. (2004). Data on Zheltovsky tephras are based on unpublished XRF analyses by V Ponomareva.

most remarkable bed of yellow pumice bombs and lapilli, informally called "upper coconuts," originated from one of the strongest Iliinsky eruptions. The ash-fall axis was directed to the northeast (Figure 2A).

The IL tephra bed contains charcoal and is underlain by a 2- to 5-cm-thick, organic-rich paleosol, the formation of which may have taken ~1.5 kyr (Ponomareva et al. 2001). The youngest date on this paleosol is 4570 ± 70 BP (Table 1), which has allowed to estimate the age of the IL tephra at ~4600 BP (Braitseva et al. 1997). Later, the age was roughly estimated at ~4800 BP based on a large number of coinciding dates (Ponomareva et al. 2001).

Dates obtained previously on a long-lived paleosol under the IL tephra encompass an age span from 4570 ± 70 to 5840 ± 150 BP (Table 1). Their divergence precludes using them in any averaging to obtain an IL age. In this case, we decided to average the reproducible younger dates from 2 charcoals and underlying peat and soil. The date on peat (GIN-11582) is considered to be reliable in spite of the high long-root sedge content, because the peat layer was capped by ~20 cm of IL volcanic lapilli, prohibiting penetration of younger roots. The average ^{14}C age for the IL eruption is 4858 ± 24 BP.

The OP_{tr} tephra was derived from Chasha Crater, located in the central part of the Tolmachev Dol lava plateau (Dirksen et al. 2002). This 450- to 500-m-deep and 1.3-km-wide crater was formed by a single large eruption. The tephra covered an area of 15,000 km^2 (Figure 2A), and the total volume of ejected material was estimated as 1.1 km^3 (Dirksen et al. 2002). The tephra bed consists of yellow, fine-grained, biotite-bearing ash, which is well identified in the soil-pyroclastic successions. Previously, this marker tephra was attributed to one of the Opala Volcano eruptions, which is why it was coded OP_{tr} (Braitseva et al. 1997). Its age was estimated at 4628 ± 90 BP based on 2 dates (Braitseva et al. 1997). Later, 6 more dates were published but not discussed in any detail (Dirksen et al. 2002). All the dates from the peat above and below the OP_{tr} tephra are consistent. We accept the date GIN-9692$_I$ on a bulk peat sample despite the fact that it contains 60% of long-root sedge, because the sampled peat layer is covered by *Sphagnum papillosum* Lindb. peat, so no roots could have penetrated in the lower layer. The dates on the soil seem to be outliers, probably due to long-term accumulation of the organic matter. Thus, an average age of OP_{tr} tephra can be estimated at 4609 ± 33 BP.

Two important local marker tephras were associated with the Dikii Greben' Volcano (Figure 2A). They are distinctive both visually and geochemically and help to unravel the complicated stratigraphy around Kurile Lake. Dikii Greben' is a dominantly rhyodacitic eruptive center (Bindeman and Bailey 1994) located immediately west of the Kurile Lake caldera. Dikii Greben' consists of a main lava dome (Mt. Nepriyatnaya) and a number of flank domes, occupying an area of >60 km^2 with their lava and pyroclastic flows. Dikii Greben' started to form immediately after the Kurile Lake caldera collapse, and then was active around 4400 BP (DG II) and 1600 BP (DG III) (Ponomareva et al. 2006).

The DGII tephra was dated mostly from peat samples and overlying soils. The date discrepancy is significant. To clear up this case, we analyzed thoroughly the plant composition of dated peats. The samples 9182–9183 (Table 1) appeared the most reliable for dating: they consist of gramineous plants and mosses and do not contain long-root sedges. We excluded all the sedge-rich peat samples from the average. The dates on paleosols are considered as outliers because we consider there to be a gap in soil accumulation (samples 8114 and 8765) caused by the eruption. Thus, the average age of the DG II tephra is 4424 ± 53 BP.

The KHD marker layer is related to Khodutkinsky Crater at the northwestern foot of the Khodutka Volcano (Figure 2B). The total volume of the KHD tephra was estimated at ~1.5 km^3 (Melekestsev et al. 1996a). Fall deposits are yellowish coarse ash with pumice lapilli and bombs, and the ash-fall axis was directed to the southwest (Figure 2B). The KHD tephra is an important marker layer for the southernmost part of Kamchatka and the Northern Kurile Islands. Earlier, the KHD tephra was dated to ~2800 BP (Braitseva et al. 1997).

The KHD tephra is dated mostly from peat and soil samples (Table 1). Two earlier published dates (Braitseva et al. 1995) proved to be outliers: one of them (GIN-4934_{Σ}) was obtained on a bulk sample from a thick peat layer, and the other one is older than the youngest reproducible dates on other peats and soils.

New dates were obtained on peat samples. The dates from peat above and beneath the KHD tephra are consistent, so for its age estimation we chose the older overlying and the younger underlying dates. Outliers resulted from a peat sample (GIN-9205) with a high content of *C. cryptocarpa*, whose roots penetrated through the thin KHD layer from the younger peat horizons. In other cases of long-root sedges occurring in peat samples, the thickness of the KHD layer was >10 cm, and according to our field observations, the roots could not penetrate through the coarse ash layer (samples GIN-8751, -9171, -9674). Thus, an average ^{14}C age for the KHD tephra is 2509 ± 32 BP. This refined age estimate is in agreement with recently published new dates for the KHD layer. Another support for this estimate is the fact that the KHD layer overlies the tephra from Avachinsky Volcano, which has an age of 2800 BP (Bazanova et al. 2005).

The most recent eruption of Dikii Greben' (DG III) produced a tephra-fall deposit, several lava domes, and a thick lava flow. In addition, east and north of the main dome 2 large lava bodies were formed, the features of which are better explained as originating from the sector collapse of the dome(s) (Ponomareva et al. 2006).

The DG III tephra is well dated from charcoals and wood enclosed within the pyroclastic layers (GIN-8117, -8118, -9154); the dates show a great consistency. Dates from underlying soil and overlying peat, marked in bold in Table 1, confirm this age. Other dates (too young/old) may result from long-root *C. cryptocarpa* in the peat sample or may reflect a long period of sandy loam accumulation. Thus, the average ^{14}C age of DG III is 1612 ± 18 BP.

Stübel Cone started to form about 1600 BP (Melekestsev et al. 1996b). Its products range from basaltic andesite to rhyolite. Fall deposits of the $KSht_1$ eruption are heterogeneous and consist of 2 sub-units: the lower sub-unit is composed of black scoria bombs and lapilli of basaltic andesite, whereas the upper sub-unit comprises white, pink, and yellow dacitic to rhyolitic pumice bombs. The ash-fall axis was directed to the southwest, so the $KSht_1$ is an important marker not only for South Kamchatka but for the Northern Kurile Islands as well (Figure 2C).

We obtained different dates on various samples (Table 1). The most reliable dates are those on peat samples composed of rootless *Sphagnum* and *Bryales* mosses (GIN-9233-9234). We selected the younger date from under the $KSht_1$ layer and the older one from above. Dates on bulk samples may reflect the mean ages of a thick soil/peat layer underlying the $KSht_1$ tephra. Samples GIN-8747 and -8748, composed of long-root *Carex* species (*C. vesicata*), seem to be contaminated by younger carbon. The average ^{14}C age of the $KSht_1$ marker bed is 975 ± 35 BP.

Kambalny Volcano produced a large phreatic eruption whose tephra were dispersed towards the southernmost part of Kamchatka and the Northern Kurile Islands (Figure 2C). We collected samples for dating from the peat sections near the source and on Shumshu Island. Due to the thickness of this tephra layer, and probably due to its chemical composition and resulting change of bog vegetation (Table 1), the gap between "underlying" and "overlying" dates is substantial. Therefore, to estimate the age of this eruption we selected only the "underlying" dates obtained from moss peat. This yielded an average ^{14}C age for KMB_{phr} of 696 ± 54 BP.

Zheltovsky Volcano produced a number of explosive eruptions during the Holocene. Tephras of 2 eruptions can be used as markers, especially for studies of tsunami deposits and beach ridges along the Pacific coast. An older eruption (ZH_1) produced minor fallout, large block-and-ash flow, and related lahars towards the Pacific coast. Its tephra is a pinkish coarse to fine ash. Most of the dates were obtained from sandy loams, and only one from organic-rich soil, all underlying the tephra horizon. Thus, we selected the youngest dates from this data set to estimate the average age of the eruption as 499 ± 19 BP (Table 1).

The most recent tephra (ZH; Figure 2C, Table 2) immediately underlies the 1907 tephra from Ksudach and was likely related to an eruption in the early 1800s mentioned in the record (Novograblenov 1932). The date 180 ± 40 BP ($GIN\text{-}4924_I$) on the underlying soil does not contradict this conclusion. This tephra consists of heavy sub-rounded basaltic lapilli rich in allivalite and eucrite inclusions.

CONCLUSIONS

In analyzing the origin of ^{14}C samples, their composition, and the stratigraphic relationships with the dated marker tephra layers, we carefully analyzed the most reliable measurements from large data sets to add precision to the ^{14}C age of a series of volcanic events within the Kamchatka Peninsula.

Dated key-marker tephra horizons record the largest explosive eruptions of South Kamchatka volcanoes and can be used for dating both volcanic and nonvolcanic landforms and deposits (e.g. paleotsunami sands; landslides; marine, lacustrine, and river terraces; beach ridges; Holocene moraines; etc.). They also provide a useful tool for paleoclimatic research based on peat bog and lake core studies.

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