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THE IMPORTANCE OF RADIOCARBON DATES AND TEPHRA FOR DEVELOPING CHRONOLOGIES OF HOLOCENE ENVIRONMENTAL CHANGES FROM LAKE SEDIMENTS, NORTH FAR EAST

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Developing continuous chronologies of paleoenvironmental change in northern areas of the Far East using ^{14}C can be problematic because of the low organic content in lake sediments. However, Holocene age-models can be supplemented by widespread tephra deposits reported in the Magadan region. The best documented of these tephras has been correlated to the KO tephra from southern Kamchatka dated to 7600 BP. Although a key chronostratigraphic marker, no detailed compendium of the distribution of this tephra and its associated ^{14}C dates has been available from sites in the northern Far East. We provide such a summary. Known locally as the Elikchan tephra, lake cores indicate an ash fall that extended ~1800 km north of the Kamchatkan caldera with a ~500 km wide trajectory in the Magadan region. Other Holocene tephras preserved in lake sediments have poorer age control and possibly date to ~2500 BP, ~2700 BP and ~6000 BP. These ashes seem to be restricted to coastal or near-coastal sites. A single record of a ~25,000 BP tephra has also been documented ~100 km to the northeast of Magadan.

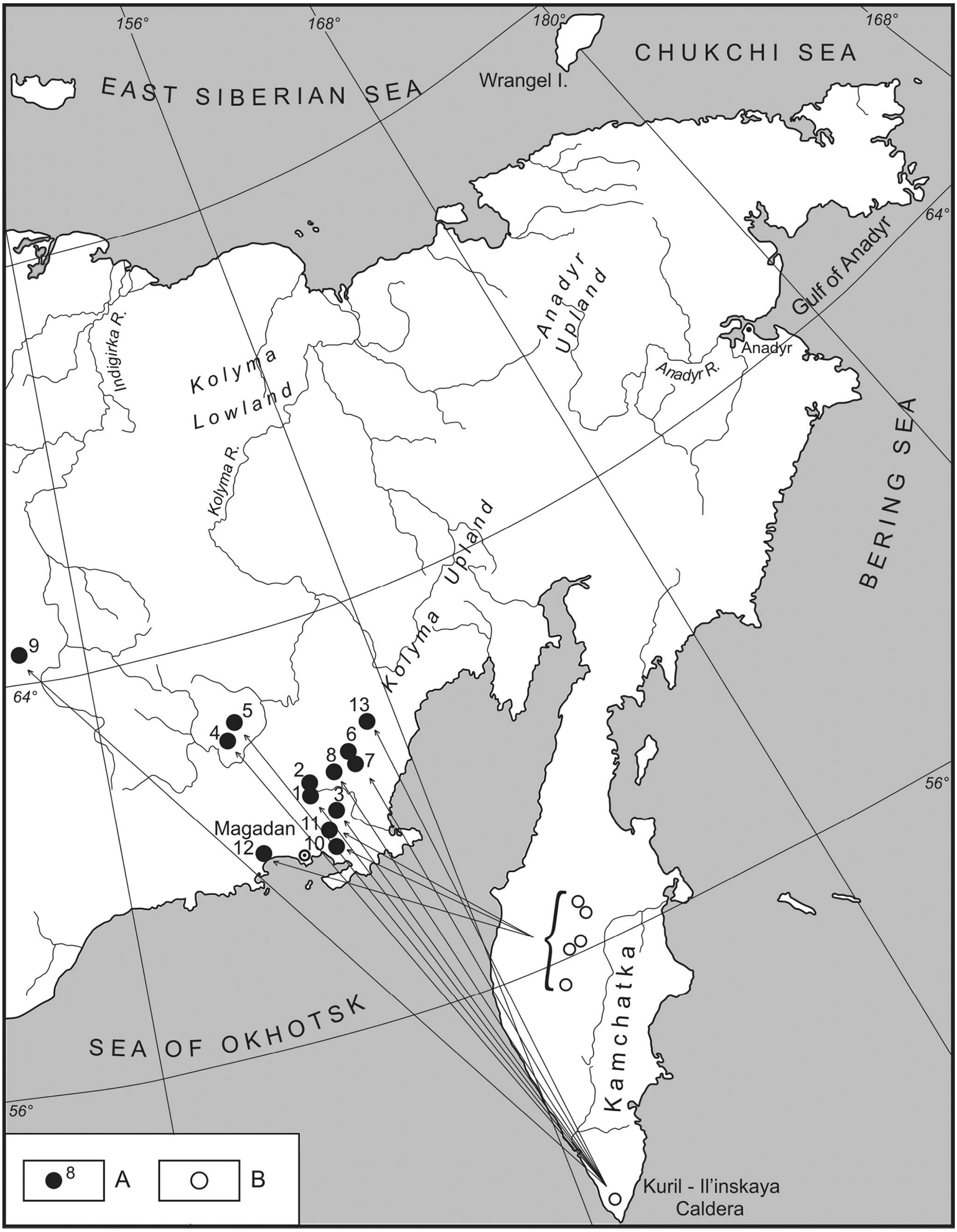
Key words: **tephra, chronology, lake sediments, radiocarbon dates, Holocene, Far East of Russia.**

INTRODUCTION

Paleobotanical studies of lake sediments in Northeast Siberia (Fig. 1) have formed the primary foundation on which late Pleistocene and Holocene climate and vegetation histories have been reconstructed, including defining the temporal boundaries of environmental changes and documenting the compositional and distributional shifts of past plant communities [3, 13, 20, 31]. Such interpretations rely equally on the quality of the proxy data, the continuity of the paleo-records, and the reliability of the chronologies. The latter can be a particular challenge when radiocarbon-dating records from northern high latitudes where: 1) sediments are often organic-poor causing a greater reliance on bulk samples that may encompass 100's of years; 2) organic material can have a long residence-time on the landscape before its final deposition in a sedimentary basin and/or uptake by aquatic organisms thereby yielding «too old» ages; and 3) plant macrofossils, particularly in lake sediments, are often sparse and fragmentary, thus limiting their consistent use

Fig. 1. Location of lakes and source areas for tephras. Dark circles indicate location of lakes (A), whereas open circles are volcanoes (B). Volcanoes of western Kamchatka reflect possible source areas, whereas the Kuril Lake-Ilinsky caldera is the definite source of the Elikchan/KO tephra.

The key to the sites is: 1 – Elikchan-1 Lake; 2 – Elikchan-4 and Elikchan-3 lakes; 3 – Alut Lake; 4 – Elgennya Lake; 5 – Jack London and Sosednee lakes; 6 – Goluboye Lake; 7 – Tschuchye Lake; 8 – Priyatnoye Lake; 9 – Smorodinovoye Lake; 10 – Lesnoye Lake; 11 – Podkova Lake; 12 – Glukhoye Lake; 13 – Julietta Lake.



156°
168°
180°
168°
EAST SIBERIAN SEA
CHUKCHI SEA
Wrangel I.
64°
Gulf of Anadyr
Anadyr Upland
Anadyr
Anadyr R.
Indigirka R.
Kolyma Lowland
Kolyma R.
Kolyma Upland
BERING SEA
9
64°
13
5
4
6
8
7
2
1
3
Magadan
11
12
10
56°
Kamchatka
SEA OF OKHOTSK
56°
8
A
B
Kuril - Il'inskaya Caldera

in dating a record and/or potentially leading to questions about sample size on dating results [1, 34, 35]. Wanting to optimize additional dating techniques, other radiometric methods, such as thermo- or optical luminescence and tephrochronology, have been used in northern areas of the Far East. Luminescence analyses have been limited typically to records that exceed radiocarbon limits [21]. Tephrochronology, however, has played a greater role in developing age models in far northeast Asian.

Tephra deposits, although not abundant, have been long-noted in studies of alluvial, paleosol, and peat sections and archeological sites of the Magadan region. In the early investigations, Holocene ashes did not correlate geochemically and/or chronologically with tephra from Kamchatka, their likely source area, and consequently these tephras were considered chronological unreliable, possibly due to reworking of material used in radiocarbon dating and/or post-depositional weathering/mixing of tephra horizons [5, 32]. Lozhkin discovered well-preserved and unmixed tephra layers that could be aged through both radiocarbon and geochemical correlation. The most ubiquitous and well-documented of these horizons was initially called the Elikchan tephra and estimated to be of mid-Holocene age [24]. Subsequent research indicated that the ash correlated with the 7600 BP Kuril Lake-Il'inskaya caldera-forming eruption from southern Kamchatka (KO tephra) [36, 32]. Although the Elikchan/KO tephra is a key regional chronostratigraphic marker, there has been no detailed publication concerning its distribution and associated radiocarbon dates in the northern Far East. Given that its importance as a well-established temporal horizon, we review here the discovery, identification, distribution, and depositional characteristics of the Elikchan tephra. We also briefly review information on other Holocene-late Pleistocene tephras from the Magadan-upper Kolyma-upper Indigirka region (herein shortened to the Magadan region). These ashes are less well known but are of equal importance for the development of dependable site and regional age-models. Because of concerns over the reliability of tephra deposits in nonlacustrine deposits, we focus our discussion on lake records.

DESCRIPTIVE BACKGROUND

The initial documentation of tephra deposits in the Magadan region was limited to those found in exposed sections and archeological sites. One of the most striking of these early discoveries is that near Steklo'nyi (~70 km to the north of Magadan). The exposure is ~300 m long and ~150 m wide, and ash thickness averages 10 m with maxima of 20–25 m [32]. This tephra was sufficiently abundant to be mined for glass production prior to World War II. Scientific investigations of this deposit began in the 1940s, and although its age is uncertain it is thought to date to the Middle Pleistocene. Other tephra layers, primarily dating to the Holocene, were more modest in their thicknesses and varied from several mm to tens of cm.

The systematic investigation of tephra in the Magadan region did not begin until the late 1980's, spurred in part by the discovery of well-preserved tephra in lacustrine cores. In addition to the Elikchan tephra, at least one and possibly three additional Holocene tephras have been documented in lake cores [4, 6–8, 25]. Although volcanic ashes have been found in other areas of the northern Far East, particularly to the northeast of Kamchatka, only the Magadan region has ash deposits of Holocene age [37].

The Elikchan Tephra, First Documentation

The Elikchan tephra is the most intensively studied ash in the Magadan region, and Elikchan-4 Lake can be considered as a «type» site. As such, we provide a more detailed description of its first discovery in the Elikchan area; characteristics of other lake sites are summarized in Results.

The first discovery of bands of volcanic ash in lake sediments of the northern Far East occurred in 1984 in a valley in the Maymandzha Mountains. This valley is characterized by low relief and straddles the watershed that separates the Upper Kolyma and Sea of Okhotsk drainages. Tectonic activity was probably responsible for the formation of a series of four lakes that straddle the drainage divide [24]. Elikchan-1 Lake lies within a relatively broad area of the valley and has a small outlet stream that flows to the Maltan River, a tributary to the Kolyma drainage. Elikchan-3 and Elikchan-4 lakes, ~1 km to the south of Elikchan-1 Lake, are connected by a small stream and are part of the Okhotsk basin. Sediment cores from Elikchan-1, Elikchan-3, and Elikchan-4 lakes (Fig. 1, Table 1) all showed a distinctive layer of whitish tephra that was informally named the Elikchan tephra.

Two cores of 162 cm length were recovered from the center of Elikchan-1 Lake. The lacustrine sediments are characterized by organic-rich layers of gray silt. The cores terminated in brown fibrous *Sphagnum* peat. This peat was radiocarbon dated to 8500 ± 100 BP and 8800 ± 100 BP, thereby providing limiting ages on the volcanic ash that was found ~15 cm above the peat (Fig. 2; Table 2). The development of the lake over a peat was particularly fortunate, because at that time radiocarbon dating in Magadan relied on liquid scintillation. This method required comparatively large-sized samples that were relatively rich in organic material, something not common in lake sediments.

Table 1. Characteristics of Lake Sites with Elikchan/KO Tephra.

Site name	Latitude, longitude, elevation (asl)	Tephra thickness (cm)	Lake dimensions (length x width, m), water depth at coring site (m)	Bracketing dates	Refe-rence
Alut	60°08'12″ N, 152°19´46″ E, 480 m	2	2000 × 400, 8	7060 ± 60, 7870 ± 70	7
Elikchan 1	60º45'11" N, 151º46'39" E, 793 m	2	900 × 700, 4	None, 8500 ± 100	30
Elikchan 3	60 º 45 '11" N 151 º 46' 39" E 824 m	1–15	1000 × 450, 10	none	29
Elikchan 4	60º45'11" N, 151º46'39" E, 810 m	1–6	3900 × 900–1300, 9	5700 ± 60, 8870 ± 60	24; 2
Tschuchye	61°02'N, 152°20' E, 750 m	3	500 × 200, 6	6480 ± 110, 8900 ± 130	11
Chernoye	61°02' N, 151°43' E, 854 m	3	1250 × 750, 5	none	28
Priyatnoye	61°02' N, 151°43' E, 893 m	14	800 × 200, 3.5	6370 ± 50, 9250 ± 50	28
Goluboye	61°07' N, 152°16' E, 810 m	12	600 × 350, 9.5	7280 ± 60, 8030 ± 240	11
Julietta	61°12' N, 153°56' E, 880 m	0.2	450 × 250, 6	Core top, 8230 ± 35	10
Elgennya	62°05' N, 149°00' E, 1040 m	1.3	4300 × 2200, 14.25	5320 ± 60, 11.040 ± 60	5
Jack London	62°10' N, 149° 30' E, 820 m	3	9500 × 4000, 16.5	8350 ± 85, 9070 ± 150 8300 ± 85	26
Smorodinovoye	64°46' N, 141°07' E, 800 m	0.1	1100 × 250, 8.5	5920 ± 130, 6840 ± 150	9
Late Holocene tephra					
Podkova	59°57' N, 152°06' E, 660 m	0.2	1000 × 500, 8.5	2580 ± 90, 3840 ± 60	8
Lesnoye	59°35' N, 151°52' E, 96 m	1	360 ×320, 5	1060 ± 60, 2900 ± 60	6
Glukhoye	59°45' N, 149°55' E, 10 m	Irregular sized nodules between 13–42 cm	4300 × 3200	none	4
Late Pleisto-cene tephra					
Alut	60°08'12″ N, 152°19' 6″ E, 480 m	0.3	2000 × 400, 8	24.970 ± 260, 27.480 ± 210	7

During that same field season, a 535-cm-long core of gray silt was recovered in 10 m of water from the center of Elikchan-3 Lake [29]. A white volcanic ash mixed with plant fragments was found at 135-150 cm core-depth and represents the thickest ash layer found in any of the lakes in the Magadan region. Additional cores were collected from Elikchan-3 at water depths of 5–7 m, and they also showed bands of volcanic ash (core depths of 142–147.7 cm). Tephra thickness varied in these cores from ~1 to 15 cm, and unlike Elikchan-1 the ash was more dispersed and did not always form a distinctive layer. Although no radiocarbon dates were obtained, pollen analysis of the first core indicates a shift at 250 cm from graminoid to shrub dominated communities. This vegetation change had been dated elsewhere to 12.300 ± 70 BP, thus supporting a Holocene age for the tephra suggested by the Elikchan-1 data [26, 27].

Elikchan-4 (also known as Grand Lake) has been the most intensively studied of this suite of lakes. The initial core was ~9.5 m long, dominated by silts, with a white volcanic ash between 213 and 214.5 cm. A joint Russian-U.S. coring expedition returned to the lake in 1989 and 1991 and raised additional cores, all containing the tephra, which ranged in thickness from 1–2 cm up to 5.5–6 cm, reflecting sedimentation variability within different sub-basins of the lake. A series of radiocarbon ages from the 1991 core, which combined conventional and AMS dates, provided the best chronological control for the Elikchan records with bracketing dates on plant macrofossils of 8870 ± 60 BP and 5520 ± 60 BP at 12 cm and 55 cm below and above the tephra, respectively.

A fourth site, Chernoye Lake, was sampled during the 1984 field season. This lake is ~30 km to the east of the Elikchan valley. Although likely originating as a thermokarst lake within a tectonic depression, the nearby hills prevented its migration across the landscape, the latter a typical process in permafrost areas. Once the lake achieved a sufficient water depth, the basin stabilized and normal sedimentation processes occurred. Lacustrine sediments of 285 cm thickness were recovered in 4.6 m

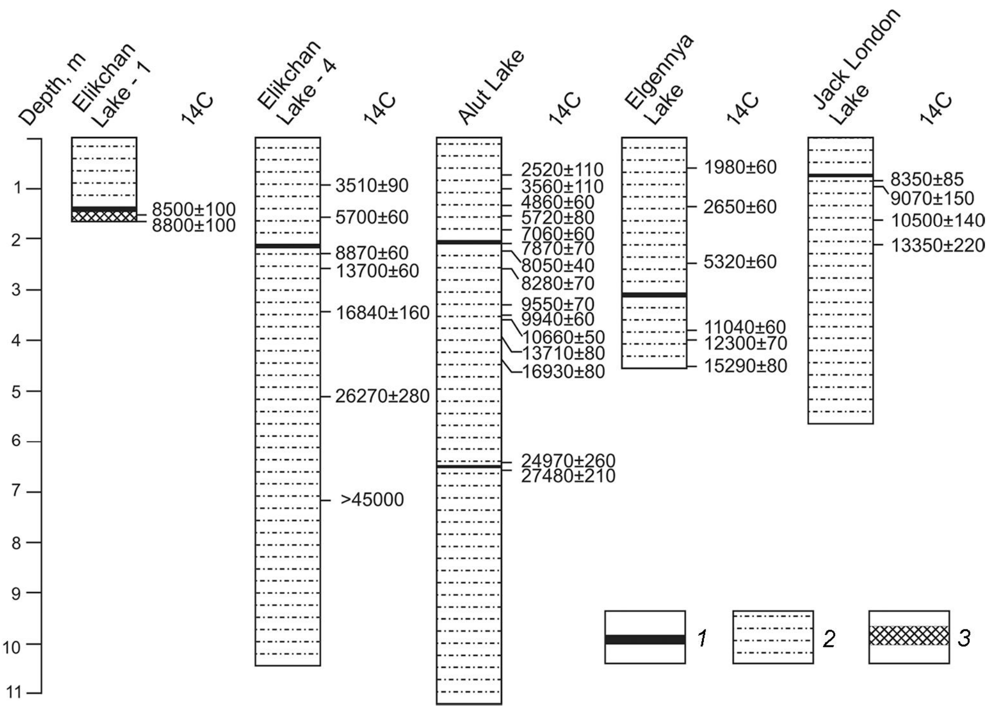


Fig. 2. Stratigraphic columns showing the location of Elikchan tephra and radiocarbon dates.

Key to the sediment types: *1* – tephra; *2* – lacustrine silt; *3* – peat. See Table 2 for more details. A stratigraphic column is not included for Julietta Lake because of poor dating control and the thinness of the tephra.

of water. The core included a whitish gray tephra at 205–208 cm. Although undated, the Chernoye record demonstrated that the ash fall extended well into the Kolyma drainage.

RESULTS

This section describes the characteristics, origin, age, and distribution of the Elikchan tephra followed by a summary of other more poorly defined Holocene and late Pleistocene tephras from the Magadan region (Figs 2 and 3, Tables 1 and 2).

Geochemical Characteristics of the Elikchan Tephra

The Elikchan tephra is typically bright white in color, although it sometimes has a grayish tint if humics have become included in the deposit or yellowish if stained by iron oxides. Granulometric composition indicates the ash is silty and pellitic with an admixture of fine-grained sand. The dominant grain size is 0.071 mm (72.4–79.7 %) [32]. The small size of the ash particles and their well sorted nature indicate wind transport far from the eruption site. Chemical analysis of the tephra from the Elikchan lakes indicates a rhyolitic composition (Table 3). SiO_2 dominates the ash with the remainder formed by plagioclase and metalic elements. Glass particles are flat and platelike and are abundant in the tephra (45–50 %). The rest of the sample consists of 30–35 % pumice fragments and 20–25 % sharp-edged fragments of ruptured gas bubbles. Additional chemical and physical characteristics of KO deposits are described by Ponomareva et al. [36] and Sakhno et al. [37].

Origin of the Elikchan Tephra

The northern Pacific Rim offers several potential source areas for the Elikchan tephra, with the nearest, albeit 1000^+ km distant, being the volcanoes of Kamchatka. Logic also suggests that a catastrophic eruption, such as one associated with caldera formation (Table 4), would be needed to produce a sufficiently large ash fall. Geochemical characteristics did indeed show that the rhyolitic Elikchan tephra represents a distal ash fall from a dramatic explosion that formed the 7-km-wide Kuril Lake-Il'inskaya caldera in southern Kamchatka Peninsula [32, 16, 18, 36; Fig. 1). Known as the KO tephra, this event represents the largest Kamchatkan eruption during the Holocene and one of the largest Holocene eruptions on earth, producing ~70 km^3 of tephra with a maximum dispersal of ~3 million km^2 [15, 36]. This event laid waste to the southern Peninsula and possibly impacted global climates [36]. Braitseva et al. [19] proposed that the KO event was extensive enough to be registered in the GISP2 ice core, corresponding to acid peaks at 6470–6476 BC. The KO eruption occurred

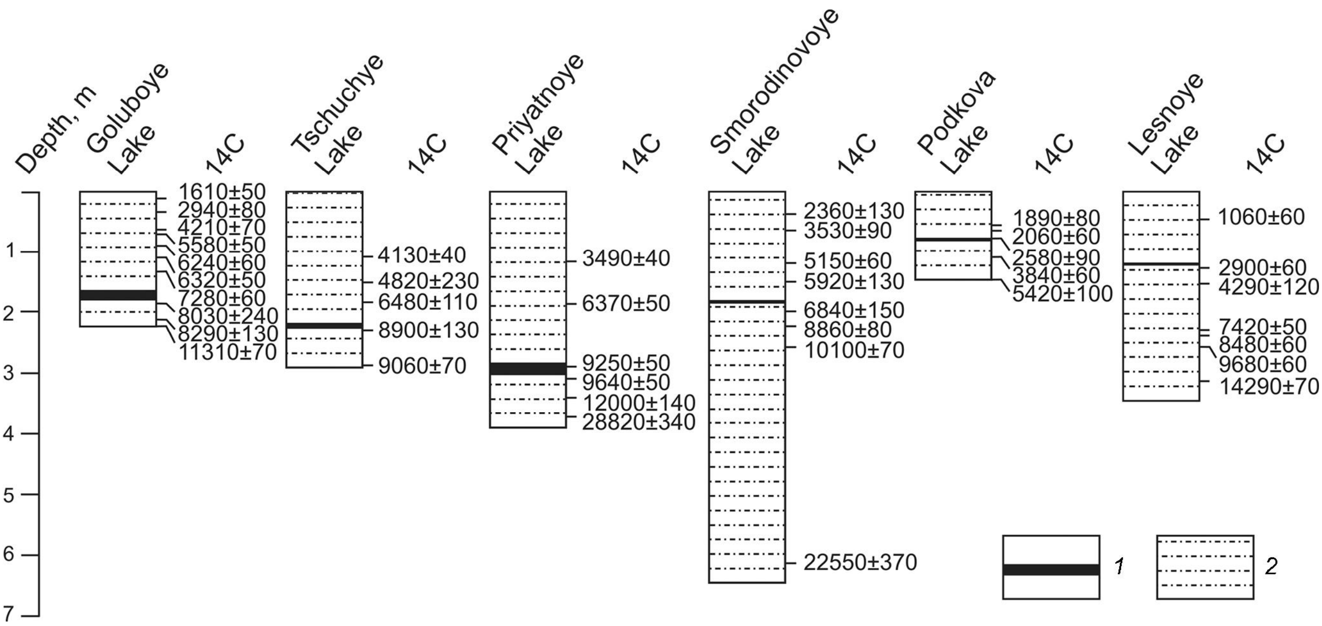


Fig. 3. Stratigraphic columns showing the location of tephra and radiocarbon dates.

Key to the sediment types: *1* – tephra; *2* – lacustrine silt. The Elikchan tephra is shown for Goluboye, Tschuchye, Priyatnoye, and Smorodinovoye lakes. The tephra in Podkova and Lesnoye lakes is from a late Holocene eruption. A stratigraphic column for Glukhoye Lake is not shown because the record is undated.

within a period of particularly active volcanism between 6600–6400 BC with a total volume of tephra deposits of at least 245–292 km^3 [33]. Melekestev et al. [32] were the first to correlate the distinctive tephra from Priokhot'ye with the KO tephra.

Determining the Age of the Elikchan/KO Tephra

The earliest age assignment for the KO tephra in southern Kamchatka was based on relative stratigraphy of the ash layer, which was found above late Pleistocene glacial deposits [14]. By the 1970s, a range of dates from 7600–9500 BP were listed for the tephra, although uncertain sample stratigraphy resulted in questionable age assignments. However, radiocarbon dates of 8000 BP (above) and 8300 BP (below) on charred wood and a paleosol, respectively, associated with the Kurile Lake ignimbrite provided one of the best age estimates [36]. Additional radiocarbon dates subsequently led Braitseva et al. [16] to propose an age of 7666 ± 12 BP. Because of the importance of the KO tephra as a regional horizon marker and the ambiguity in previous results, new samples from both proximal and distal locales were obtained and radiocarbon dated [36]. Fourteen radiocarbon samples resulted in an average age of 7618 ± 14 BP for the KO tephra.

Assessing the age of the Elikchan tephra followed a similar iteration as in Kamchatka. Relative sedimentary (i.e., above glacial deposits) and pollen stratigraphy (younger than full- or late glacial assemblages dominated by herbs and shrub birch, respectively) placed the tephra within the Holocene. Continued field research in the Magadan region provided a suite of radiocarbon dates on buried peats, varying in age from 6200–7700 BP [32]. Although many of these deposits did not contain the tephra, the available ages and stratigraphic relationships allowed Melekestsev et al. to propose a ~7700 BP age for the ash, and the geochemistry of this tephra suggested the Kurile Lake-Il'inskaya caldera as the source. The first absolute age control from lacustrine sediments was provided by radiocarbon dates from Elikchan-1, Elikchan-4, and Jack London lakes. Simple linear interpolation age models suggested that the tephra was closer to 8200–8300 BP, consistent with that on the Kurile Lake ignimbrite although not comparable to the ~7600 BP age proposed by Braitseva et al. [16].

Lozhkin then examined an expanded set of sites and radiocarbon dates including an 1124-cm-long core from Alut Lake. This core is dominated by silt that included numerous plant remains (e.g., grass, terrestrial and aquatic moss, conifer needles, larch branches, larch cone, birch and alder seeds). Such an abundance of macrofossils is not typical of lakes in Northeast Siberia. The Alut core, thus, provided an exceptional opportunity for dating the Elikchan ash (203–205 cm core depth). Well-preserved larch twigs, one with an attached cone, were found directly below the tephra. The cone was dated to 7870 ± 70 BP and the attached branch to 7850 ± 60 BP. Other

Table 2. Summary of Radiocarbon Dates Used in Age Models.

Lake name (tephra depth in core, cm)	Radiocarbon age	Sample depth (cm)	Material dated	Lab number
Elikchan 1 (140–142)	8500 ± 100	155–157	*Sphagnum* peat	MAG-876
	8800 ± 100	160–162	*Sphagnum* peat	MAG-875
Elikchan-4 (213–214.5)	3510 ± 90	85–95	bulk sediments	BETA-59380
	5700 ± 60	150–158	humic acid	CAMS-14601
	8870 ± 60	226–228	unidentifiable plant remains	CAMS-14599
	13.700 ± 60	250–260	bulk sediments	CAMS-6046/ BETA-61558
	16.840 ± 160	340–350	humic acid	CAMS-14603
	26.270 ± 280	505–515	bulk sediment	CAMS-6047/ BETA-59381
Alut (203–205)	2520 ± 110	73–75	larch needle, charcoal, unidentified leaf cone scale,	CAMS-43423
	3560 ± 110	101–102	aquatic moss graminoid and	CAMS-43424
	4860 ± 80	130–134	terrestrial moss stems larch needle,	CAMS-45347
	5720 ± 80	150–153	unidentified leaf unidentifiable plant remains	CAMS-45348
	7060 ± 60	180–182	larch cone larch twig	CAMS-32942
	7870 ± 70	205	larch twig	CAMS-31252
	7850 ± 70	205	larch twig	CAMS-31253
	7930 ±90	205	wood	CAMS-32687
	7970 ± 60	205	conifer needle, leafy fragments	CAMS-32688
	8050 ± 40	219–220	unidentifiable	CAMS-43425
	8280 ±70	255–258	plant remains larch needle, birch or alder	CAMS-45349
	9550 ± 70	325–327	seeds aquatic moss aquatic moss	CAMS-32943
	9540 ± 60	327-330	moss stems aquatic moss	CAMS-45350
	10.660 ± 50	355–356	willow bud, moss, unidentified	CAMS-45352
	13.710 ± 80	375–376	seed	CAMS-43430
	16.930 ± 80	410–412		CAMS-57056
	24.970 ± 260	645–646		CAMS-44516
	27.480 ± 210	656–658		CAMS-45353
Elgennya (308.6–309.9)	1980 ± 60	58–60	terrestrial plant remains	CAMS-14586
	2650 ± 60	134–136	terrestrial plant remains	CAMS-14605
	5320 ± 60	248–250	terrestrial plant remains	CAMS-14606
	11.040 ± 60	377–380	terrestrial plant remains	CAMS-14608
	12.300 ± 70	398–400	terrestrial plant remains	CAMS-14587
	15.290 ± 80	452–454	terrestrial plant remains	CAMS-14589
Jack London (72–75)	8350 ± 85	74–77	unidentifiable plant and insect remains	WHG-819/AA-6883
	9070 ± 150	83–92	bulk sediment	BETA-42586
	10.500 ± 140	148–160	bulk sediment	BETA-42587
	13.350 ± 220	198–207	bulk sediment	BETA-43472

Table 2. (Contd.).

Lake name (tephra depth in core, cm)	Radiocarbon age	Sample depth (cm)	Material dated	Lab number
Goluboye (161–173)	1610 ± 50	8–10	unidentifiable plant remains	CAMS-43432
	2940 ± 80	32–33	terrestrial moss	CAMS-32941
	4210 ± 70	57–60	larch needles	CAMS-43426
	5580 ± 50	64–65	moss stems and leaves	CAMS-57057
	6240 ± 60	75-76	aquatic moss	CAMS-44358
	6320 ±50	104–105	aquatic moss	CAMS-46223
	7280 ± 60	125–127	moss stems	CAMS-55827
	8030 ± 240	178–180	wood	CAMS-44518
	8290 ± 130	204–206	unidentifiable plant remains	CAMS-53250
	11.310 ± 70	211–212	graminoid stems	CAMS-52335
Tschuchye (212–215)	4310 ± 40	107–112	wood and insect remains	CAMS-49494
	4820 ± 230	145–147	birch leaf	CAMS-52339
	6480 ± 110	179–181	larch needle	CAMS-54892
	8900 ± 130	221–226	larch needle and insect remains birch and alder seeds	CAMS-49695
	9060 ± 70	283–285		CAMS-50339
Priyatnoye (277–291)	3490 ± 40	111–112	terrestrial moss, leaves, stems	CAMS-52336
	6370 ± 50	180–181	larch needles, twig larch	CAMS-52337
	9250 ± 50	277–278	needle, unidentifiable plant remains	CAMS-46230
	9640 ± 50	301–302	moss	CAMS-53248
	12.000 ± 140	352–353	wood, conifer	CAMS-53249
	28.820 ± 340	362–365	needle semiwoody material	CAMS-50336
Julietta (128.6–128.8)	8230 ± 35	145–145.5	wood	CAMS-103338
	12.200 ± 40	199–201	wood, aquatic moss	CAMS-103339
	13.880 ± 130	218–220	bulk sediment	CAMS-128576
	19.140 ± 350	250–252	bulk sediment	CAMS-128577
	21.170 ± 570	440–443	bulk sediment	CAMS-128579
Smorodinovoye (170–170.1)	2360 ± 130	24–26	wood	CAMS-43433
	3530 ± 90	50–52	seed bracts, birch *Daphnia* eggs	CAMS-44519
	5150 ± 60	107–108	moss stems	CAMS-57058
	5920 ± 130	135–137	*Daphnia* eggs,	CAMS-44520
	6840 ± 150	180–185	insect remains wood and larch	CAMS-46240
	8860 ± 80	205–209	needles	CAMS-58289
	10.100 ± 70	245–246	insect remains	CAMS-58290
Podkova (72–72.2)	1890 ± 80	49–50	unidentifiable plant fragments	CAMS-32944
	2060 ± 60	56–57	larch needles	CAMS32945
	2580 ± 90	66–68	larch needles	CAMS-32946
	3840 ± 60	100–101	wood	CAMS-46288
	5420 ± 100	136–138	pine needles	CAMS-32690
Lesnoye (109–110)	1060 ± 60	30–35	unidentifiable plant remains	CAMS-29163
	2900 ± 60	110–115	wood	CAMS-18070
	4290 ± 120	140–142	larch needle	CAMS-27445
	7420 ± 50	215–220	wood	CAMS-18063
	8480 ± 60	225–226	larch needles, wood	CAMS-27444
	9680 ± 60	243–248	wood	CAMS-18065
	14.290 ± 70	320–330	wood, charcoal	CAMS-27443

Table 3. Examples of Elemental Composition (% wt) of the Elikchan/KO distal tephra (Kamchatka and Magadan Region) and Late Holocene Tephra (Magadan Region).

Sample	98KAM7[a]	MAG-1[b]	CKB-2[c]	Elikchan lakes[d]	Lesnoye Lake[e]	Port Magadan[f]
SiO_2	76.27–77.5	76.2	76.31	72–76	74.2	67.35
TiO_2	0.19–0.25	0.24	0.24	0.26–0.27	0.26	0.95
Al_2O_3	12.5–13.3	13.53	13.28	13.18–13.9	13.5	12.18
FeO/Fe_2O_3	1.43–1.56	1.56	1.53	1.89–1.94	1.99	4.87
MnO	0.05–0.07	0.05	0.07	0.07	0.06	0.08
MgO	0.23–0.28	0.32	0.27	0.17–0.37	0.37	1.26
CaO	1.37–1.5	1.62	1.58	1.86–1.97	1.75	2.69
Na_2O	4.38–4.63	4.24	4.34	4.02–4.38	4.76	3.02
K_2O	2.03-2.13	2.02	2.04	1.88–1.94	-	1.98
F	0.02–0.06	0.03	0.06	-	-	-
Cl	0.13–0.15	0.15	0.15	-	-	-
P_2O_5	0.01–0.03	0.04	0.05	0.03–0.05	0.05	-
SO_2	0.01–0.02	0.01	0.02	-	-	-
LOI	-	-	-	-	1.05	4.69

a – pumice fall layer 50 km north of Kurile Lake (KO) caldera, range of 3 samples (microprobe analysis from Ponomareva et al., [36]); b – Elikchan/KO ash from Magadan region, ~1000 northwest of caldera (microprobe analysis from Ponomareva et al. [36]); c – Elikchan/KO ash from Elikchan-4 Lake (microprobe analysis from Ponomareva et al., 2004); d – Elikchan/KO ash from Elikchan-1, Elikchan-2, and Elikchan-4 lakes, range of 3 samples 32]; e – Lozhkin unpublished data; f – from Sakhno et al. [37].

samples of the branches found at the same depth dated to 7930 ± 90 BP and 7970 ± 60 BP. With this improved dating control from Alut and other lakes, Anderson et al. [7] independently arrived at an age of 7650 ± 50 BP for the Elikchan tephra.

Distribution of the Elikchan Tephra

As discussed above, the first systematic documentation of the Elikchan tephra was in sites from northern Priokhot'ye and the southern edge of the Kolyma basin. These initial investigations suggested that the ash fall was of sufficient intensity to cross over the 1800–2000-m-high Anachag Ranges that separate the Okhotsk and Kolyma drainages. Subsequent analysis of lake records expanded the tephra's occurrence to both the east and north of the initial research area as described below.

Besides the Elikchan lakes, Alut is the only lake in northern Priokhot'ye to include the Elikchan tephra [7]. Located in the northern Bilibin Range (elevations of up to 900 m) near the Okhotsk Sea coast, the lake lies in a narrow north-south trending valley. Alut Lake was formed behind a landslide perhaps triggered by seismic activity. The core is characterized by horizontal layers of gray and dark gray silt with a 2-cm-thick ash layer. As stated previously, the core included numerous plant macrofossils that ultimately helped to clarify the age of the Elikchan tephra.

A set of 4 sites lie to the east of the Elikchan-Alut transect. The closest of these lakes is Priyatnoye, which is only ~200 m distance from Chernoye Lake, one of the original Elikchan tephra sites. Like Chernoye, the Priyatnoye basin has a rather complex history [23, 28]. The lake probably was formed initially during late oxygen isotope stage 3 (OIS3) in a basin constrained by moraines of OIS4 age or possibly by moraines associated with one of the cold phases of OIS3 [22]. The sediment structure in the lower part of the core reflects cryogenic influences that suggest the lake dried out or shallowed significantly during OIS2, allowing the water in the sediments to form thin ice lenses distinctive of *schlirr* structure. A radiocarbon date of 12.000 ±140 BP (CAMS-53249) and pollen spectra dominated by shrub birch indicate that sedimentation began again during the late glaciation. The collection of water in the basin and general climatic warming resulted in melting of ice in sediments bordering the lake. As this process continued, Priyatnoye Lake expanded as is characteristic of migrating thermokarst lakes. However, the surrounding moraines limited its movement, and the basin eventually stabilized providing an undisturbed Holocene palynological and sedimentary record. The Elikchan tephra is particularly thick (14 cm) at this site.

Goluboye, Tschuchye, and Julietta lakes are found to the east of the Elikchan-Priyatnoye cluster [10, 11]. All these sites are of glacial origin. Goluboye and Tschuchye, separated by ~3 km, lie in the Talaya region, whereas Julietta is within the Kigan Massif that forms a portion of the Okhotsk-Kolyma drainage divide. Goluboye is the largest of these lakes and also has the thickest tephra deposit (12 cm). It is located at the end of a 6-km-long glacial valley, and the ridges that confine the lake appear to have originated as dead-ice deposits. Tschuchye and Julietta, on the other hand, have smaller catchments and also thinner tephra layers (3 and 0.2 cm, respectively). The Julietta core represents the easternmost occurrence of the Elikchan tephra in the Magadan region.

A second set of sites, located to the northwest of the Elikchan area, straddles the Bolshoi and Malyi Annachag Ranges. Jack London and Sosednee lakes are located within Bol'shoi Annachag, whereas Elgennya Lake lies to the east between the Bol'shoi and Malyi Annachag Ranges [26, 6]. Elgennya was formed by moraines of OIS2 age. The oldest age for the moraine complex near Jack London and Sosednee lakes (although Sosednee is likely the younger lake) is still debated with possible formation during OIS2, OIS4, or perhaps during the middle Pleistocene. The discovery of the Elikchan tephra in the Jack London core represented the first evidence of the teprha's more extensive presence in the Upper Kolyma region. However, the tephra was not preserved in the Sosednee cores even though this lake immediately borders Jack London Lake. Jack London represents the largest and Elgennya the highest lake basins within which the Elikchan tephra has been documented (Table 1).

The final lake that includes the Elikchan tephra is found to the west of the Kolyma drainage. Smorodinoye Lake is located on a tributary to the Indigirka River [9]. Like the Annachag region, this area has experienced repeated glaciations, resulting in gentle hills bordering the site to the north and south. Moraines formed the current lake, and the pollen record and radiocarbon dates indicate that the lake formed during early OIS2. A thin layer of white volcanic ash (170–170.1 cm core depth) was found in the dark gray silts that typify the core. Although the tephra chemistry is consistent with the Elikchan tephra (J. Beget, personal communication), a radiocarbon date of 6840 ± 150 BP (CAMS-46240) at 180–185 cm suggests a younger volcanic event. However, an estimated age for the tephra of ~7300 BP, an age more in line with the accepted Elikchan/KO age, is indicated in an age model that discards the 6840 BP date as too young. Thus, Smordinovoye Lake likely is the northernmost record of the Elikchan tephra, representing a ~1800 km distance from the source.

Distribution, Age and Origin of other Magadan Tephras

Several years after lake studies in the Elikchan area, a Holocene-age tephra was discovered near Chistoye Lake, which lies in the central part of a small tectonic depression to the east of the city of Magadan. This depression is ringed to the northwest and south by low mountains, ranging from 400–500 m and 700–900 m, respectively. Glacial features characterize this lowland, and a modest plateau (~100 m asl) borders the Chistoye basin to the north. This plateau is part of a relatively extensive peatland that is dotted by numerous small lakes. A whitish-gray ash was recovered in a sediment core from one of these lakes (Lesnoye Lake; Figs. 1 and 2; Tables 1 and 2) [6]. Unlike the Elikchan tephra, which typically forms a well-defined layer, this ash appeared in the core as small inclusion between 109 and 110 cm. A wood fragment (110–115 cm) below the tephra was dated to 2900 ± 60 BP, indicating that the Lesnoye ash was not equivalent to the Elikchan tephra. Linear interpolation between nearest bracketing dates suggests an age of ~ 2800 BP for the tephra.

Further support for the occurrence of a late Holocene ash fall was provided by a peat exposure found ~115 m to the east of Lesnoye Lake. The section contained a thin horizontal layer that included lenses of tephra, which were similar in appearance to that in the Lesnoye core. A radiocarbon date on a bulk peat sample from that horizon yielded an age of 2745 ± 10 BP (AGI-1458), suggesting that the two ashes are likely equivalent.

Late Holocene tephra layers have been noted in Podkova and Glukhoye lakes (Figs. 1 and 2; Tables 1 and 2), although in the latter record dating control is only broadly provided by pollen stratigraphy [8. 4]. Podkova Lake is located within a complex of recessional moraines found within a glacially carved valley in the Bilbin Range. The horseshoe shape of the lake mirrors the bordering glacial moraine, and although the glacial structure is likely of late OIS2 age, the lake itself appears to date to the mid-Holocene. As at Lesnoye, which lies at a lower elevation, a clear although thin whitish gray ash was noted between 72–72.2 cm core depth with bracketing dates of 2580 ± 90 BP (66–68 cm) and 3840 ± 60 BP(100–101 cm). Simple linear interpolation yields an estimated age of 2770 BP for the ash. Like Lesnoye Lake, Glukhoye Lake is also coastal but is found to the west of Magadan. The poor chronology of the Glukhoye record limits comparison to these other tephras, but if it represents the same event, the ash also would have fallen to the west of Magadan.

Unlike the Elikchan/KO tephra, this late Holocene ash is limited to coastal lakes and appears in modest thicknesses, perhaps suggesting a smaller eruption as compared to KO. Melekestev et al. [32] suggested several volcanos in central Kamchatka as possible sources for late Holocene ashes found in coastal or near coastal exposures (Fig. 1). While questions of redeposition limit the reliability of the ages, the section data suggest the presence of at least two other Holocene ashes. A ~ 2500 BP tephra has been documented in a section near the Magadan port. However, its geochemistry differs from that of the Lesnoye tephra (the latter having 74.2 % SiO_2 and the former 67.35 %) suggestive of a second late Holocene tephra near the Okhotsk coast [37].

Another intriguing discovery is that of a light-colored tephra described from a Holocene section exposed in a quarry (59°40′ N, 151°12′ E, 40 m asl; informally known as the Tanon quarry) in northern Priokhot'ye [25]. The Holocene sediments are characterized by clay, sand, and paleosols, the latter with trees in growth positions. The tephra forms an irregular layer at ~150 cm depth in the ~2.5–3- m-thick Holocene section. The tephra varies in thickness from several mms to~10 cm and primarily appears in large lenses of up to 40 m length. A forest soil immediately overlies the tephra. A piece of wood from this level yielded a date of 5880 ± 45 (MAG-1150), suggesting the Tanon ash was younger than the Elikchan tephra. The radiocarbon date was on tree roots found in growth position, and even though the paleosol immediately overlies the ash, a "too young" date is not necessarily unexpected as there may be some time elapsed prior to the re-establishment of vegetation. However, a ~1700 yr discrepancy seems somewhat large; for example such an interval is inconsistent with what has been observed with the Elikchan tephra, where data show little disruption of the vegetation [32]. A second possibility is that this tephra corresponds to 6000 (KS_2) or 6100 BP (KS_3) eruption of the Ksudach volcano, located ~ 50 km to the northeast of the Kurile Lake-Il'inskaya caldera. The crystal characteristics of the KS_2 and KS_3 tephras are generally similar to KO and both KO and KS_3 are classified as rhyodacites [17].

Perhaps most elusive of the Northeast Siberian tephras is one with an apparent late Pleistocene age that has been documented only at Alut Lake (650.5–650.8 cm core depth). Like the younger tephras, this whitish-gray ash is of rhyolitic composition and has bracketing radiocarbon dates of 24. 970 ± 260 BP (645–646 cm core depth) and 27.480 ± 210 BP (656–658 cm core depth). The associated palynological assemblage is consistent with full-glacial spectra from other sites in Northeast Siberia that generally date between ~12.500 and 25.000 BP.

SUMMARY AND CONCLUSIONS

The need for good quality chronologies in paleoenvironmental reconstructions and data-model comparisons is well established [e.g., 39]. Holocene and late Pleistocene age-models typically are based on radiocarbon dates, but age modeling in arctoboreal areas represents specific challenges related to the predominance of organic-poor sediments and to sample size, type, and depositional history. In southern areas of the study region, age modeling has been greatly aided by the presence of a clear marker horizon originally named the Elikchan tephra and subsequently correlated to the 7600 BP KO eruption that formed the Kirill-Il'inskaya caldera in southern Kamchatka. As numbers of lake records from the Magadan region increased in the 1980's and early 1990s, it became apparent that this ash fall was widespread, thereby making the Elikchan/KO tephra a key chronostratigraphic marker. Additionally, the tephra generally showed spatial continuity within a lake basin, making it more likely that a single lake core would mark its presence. Despite its importance, no detailed compendium of tephra distribution and associated radiocarbon dates from lake sites that include the Elikchan/KO has been available from northern areas of the Far East.

Although the correlation of the Elikchan-KO tephra had been proposed in the 1990's [32], the documented spatial extent of the ash fall has expanded significantly since them. For example, the distance from the caldera in southern Kamchatka to northern Priokhot'ye and the Elikchan area is 1000-1100 km. The discovery of the tephra in the Jack London and Elgennya cores (Annachag Range) lengthened the area of the ash fall northwestward by another 250 km and eventually its recovery at Smordinovoye Lake (Upper Indigirka basin) extended the ash fall to ~1800 km distance from the caldera. Approximately 700 km separate the furthest northwestern and southeastern sites (Smordinovoye and Julietta lakes, respectively), and the greatest width between proposed trajectories is ~500 km (Glukhoye and Julietta lakes). Although future research in the Magadan region may expand the area of distribution, so far other lake sites located in other areas of northern Priokhot'ye and in the Upper Kolyma and Indigirka drainages do not contain the Elikchan/KO tephra [3]. The same is true for sites farther to the northeast in Chukotka, although other pre-Holocene ashes have been noted there [32, 37, 38].

The thickness of the Elikchan/KO tephra can vary significantly within any given lake (e.g., 1 to 15 cm thickness at Elikchan-3) reflecting both the topographic complexity of a particular basin and characteristics of the catchment (e.g., extent of over land water flow, number and size of inflow streams). Inconsistencies of preservation in nearby sites (e.g., Jack London and Sosednee lakes) have also occurred. However, from the lake data in hand, there does not appear to be any systematic relationship between: 1) lake size and presence/absence of tephra; 2) lake size and thickness of tephra; and 3) size of catchment and tephra deposition (i.e., in these lakes, the larger the lake, the greater the catchment).

Unlike the Elikchan/KO tephra, the origins of the single late Pleistocene tephra (ca. 25.000 BP) and the 2 or 3 mid- to late Holocene tephras (ca. 2700 BP, 2500 BP [?], 6000 BP [?]) are not as clear cut, because of incomplete geochemical data and questionable or inadequate radiocarbon control. For example, Sakhno et al. [37] proposed a correlation to the 3500 BP eruption at Avacha with the late Holocene tephra described for the Magadan region. The silica-rich tephra from Lesnoye Lake (74.2 %), at least, is a poor match to Avacha (51.31 % SiO_2) as is the 2700 BP (Lesnoye) or 2500 BP (Magadan) ages. The «Tanon» tephra, based on the currently available chronology, may correlate with the KS3/KS2 6000-6100 BP eruption of Ksudach volcano, but further research is needed to determine a possible correspondence.

Sakhno et al. [37], based on radiocarbon and Ar-AR dating, suggested that tephra of the Russian Far East can be categorized within 4 age groups: ~3500 BP, 7600 BP, 40.000–60.000 BP, and 160.000–180.000 BP. With the exception of the Elikchan/KO tephra, none of the lake tephras from the Magadan region fall within these groupings. These groupings also do no correspond with ages of large eruptions documented in Kamchatka, which are the likeliest sources for the Northeast Siberian tephras [17, 12]. Additional research into the identification and aging of tephras in the Magadan region is a needed next step in improving regional chronostratigraphies, a step that is greatly aided by improved analysis of small-sized samples in both radiocarbon and tephra investigations.

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Радиоуглеродные датировки и прослои вулканического пепла в осадках озер как основа для хронологии изменений природной среды севера Дальнего Востока в голоцене

Радиоуглеродная датировка непрерывных климатических летописей осадков озер, характеризующих изменение природной среды севера Дальнего Востока в голоцене, встречает определенные трудности из-за низкого содержания в осадках органики. В этой связи прекрасными реперами для хронологических построений могут быть прослои вулканического пепла. Первая находка тефры в осадках Эликчанских озер в Северном Приохотье дала основание назвать эту тефру эликчанской. Время ее выпадения сопоставляется с образованием кальдеры Курильское озеро – Ильинская на юге Камчатки 7.6 тыс. л. н. Озерные керны показывают, что вулканический пепел распространялся на 1800 км к северу от Камчатской кальдеры полосой шириной около 500 км в Северном Приохотье, в горных районах Колымы и Индигирки. Вблизи северного побережья Охотского моря в осадках ледниковых озер установлены также прослои вулканического пепла, имеющие возраст около 2.7 тыс. л. Прослой тефры, выпавшей в Северном Приохотье около 25 тыс. л. н., обнаружен в осадках оз. Алут в 100 км к северо-востоку от Магадана.

Ключевые слова: **тефра, хронология, осадки озер, радиоуглеродные датировки, голоцен, Дальний Восток России.**