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GEOLOGY

Origin of Pleistocene–Holocene Ashes of the Russian Northeast Based on Trace and Rare Earth Element Data

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Catastrophic Plinian-type eruptions with the long-range ejection of pyroclastic material occurred in northeastern Asia repeatedly in the Pleistocene–Holocene and historical time. At present, the main sources of explosive eruptions are Kamchatkan volcanoes (29 active volcanoes). Their eruptions in the Pleistocene and Holocene had a catastrophic character [1, 2, and others].

The continental part of northeastern Asia incorporates a small number of volcanoes, including the Pektousan (Baitou Shan) Volcano located at the junction of Russia, North Korea, and China. During the last catastrophic eruption more than ka ago, the volcano ejected more than 100 km^3 of trachyte tephra, which reached the islands of Japan.

Ash beds are known in some areas of the Magadan district and Chukotka. Their detailed characteristics, morphology, and radiocarbon ages are reported in the works of geologists from Magadan and Kamchatka [2, 3, and others] (Fig. 1). Based on morphology and age correlations, the Magadan ashes are attributed to catastrophic volcanic eruptions in Kamchatka [3].

Within the framework of a Joint Russian–German project, sediments of Lake El'gygytgyn were studied to determine paleoclimatic changes in the Pleistocene and Holocene. A 13-m-thick upper section of the bottom sediments was recovered. The thickness of bottom sediments in the lake caldera is 350–400 m [4, 6]. Ashes found in the borehole at depths of 2–3 and 7–8m were referred to the upper Pleistocene based on the composition of diatomaceous algae. The upper and lower horizons correspond to intervals of 40–60 and 160–180 ka ago, respectively [6]. The ashes from these horizons were kindly placed at our disposal for analysis by J. Olaf, Leipzig University, Germany.

Rhyodacite tephra of ancient and modern eruptions of the Karymsky and Sheveluch volcanoes and other eruptions of the corresponding age range were absent in our collection. Other volcanic edifices and lava flows are also known in the Russian Northeast. Based on K–Ar, Rb–Sr, and Ar–Ar datings, they were active during the following time intervals (Ma): Rudich and Dzhek volcanoes 38–35; volcano at Zhokhov Island 2.2–0.5; Aluchinskii volcanoes, their lava flows, and Bilibin Volcano 0.8–0.5; Ustiev and Balagan Tas volcanoes 0.4–0.2. These volcanoes erupted basaltic lavas (picritic and alkali basalts and basaltic andesites). The subordinate pyroclastic eruptions composed small cones [5]. The distribution of ashes of these volcanoes in the Pliocene and Pleistocene sediments of the Russian Northeast has not yet been studied. The origin of ash beds in the late Pleistocene and Holocene sediments of the Magadan district was deciphered based on the comparison of major and trace element (including REE) compositions of the Magadan and Kamchatka ashes with consideration of chronological data obtained primarily by the radiocarbon method in laboratories of the Geological Institute (Moscow) and the Northeastern Complex Research Institute (Magadan) [3, 2].

Detailed description of ash beds in the Magadan district and radiocarbon age determinations indicate their wide age range. However, the majority of ash horizons (Levaya Palatka, Lake Chistoe, Levyi Divnyi) have an age of ~ 7.6 ka [3]. The youngest volcanic ash is found in the Magadan harbor area (2.5 ka). The oldest ash (70 ka) is located in the Uptar deposit, which includes two large lenses confined to glacial and fluvioglacial sediments. The Uptar deposit (~60 m long and 7–14 m

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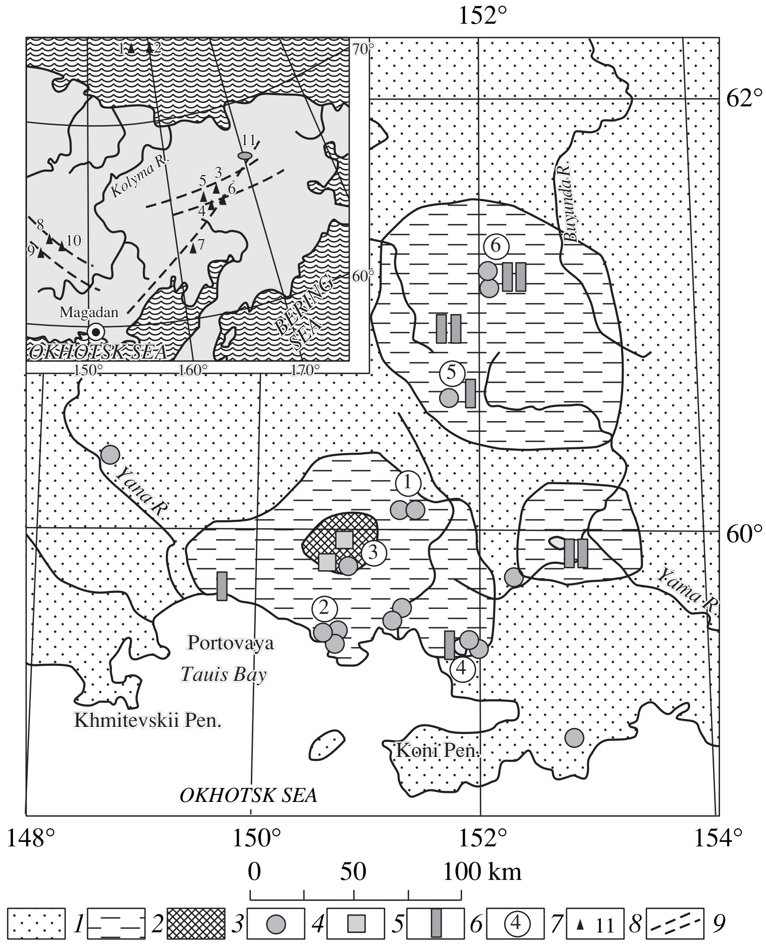

Fig. 1. Distribution of volcanic ashes in the northern Okhotsk region and location of ash sections studied by different authors [2, with additions]. (*1*) Sheetlike initially precipitated ash flows (mainly subsoil and intrasoil); (*2*) volcanic ashes redeposited in the slope, fluvial, and lacustrine sediments (overlapped); (*3*) lacustrine and glaciolacustrine lenses in the Zyryan glacial and fluvioglacial sediments; (*4–6*) location of sections containing Quaternary volcanic ashes: (*4*) natural exposures and shallow soil trenches; (*5*) cores of lacustrine sediments; (*6*) quarry wastes; (*7*) sampling sites: (1) Levaya Palatka, (2) Port Magadan; (3) Uptar, (4) Lake Chistoe, (5) Lake Grand, (6) Levyi Divnyi. Legend for the inset: (*8*) Pleistocene and Holocene volcanoes of the Russian Northeast: (1) Benetta Is., (2) Shokhov Is., (3) Ustiev, (4) Aluchinskii, (5) Pyatistennyi, (6) Bilibin, (7) Kedonskii, (8) Balagan-Tass, (9) Rudich, (10) Dzhek, (11) Lake El'gygytgyn caldera); (*9*) fault system.

thick) is composed of intercalating ashes of various tints separated by lenses of sands and gravel. Like most ash horizons [2], this deposit is referred to as redeposited ash.

For comparison, we took ashes and tephra of Kamchatkan volcanoes (caldera of Lake Kuril'skoe, Khangara, Ksudach, Zhupanov, Avachin, Gorelyi, and others). They correspond to basalts; basaltic andesites; and, in places, dacites in terms of composition.

To correlate ashes in the Russian Northeast with ashes of catastrophic volcanic eruptions in Kamchatka, we determined major components, as well as trace and rare earth elements (ICP-MS method), in them at the Vinogradov Institute of Geochemistry, Irkutsk. The obtained data made it possible to compare ashes from these areas, correlate the distribution of trace elements and REE (hereafter, trace elements) in them, and determine the indicator ratios of elements (table, Fig. 2).

Although not all Kamchatkan ashes were included in this study, we can draw the following preliminary conclusions:

(1) Based on isotope dating (^{14}C, Ar–Ar), ashes of the Russian Far East can be subdivided into five age groups (ka): 3.5; 7.6; 40, 40–60, and 160–180. Ashes with ages of 7.6 ka are most common. However, they differ in petrochemical and trace element composition (table, Fig. 2). Some analogy can be found between ashes from Levaya Palatka and Lake Chistoe, Port Magadan, and Levyi Divnyi, although ashes from the latter two areas differ in age and composition. Ashes from the Uptar deposit are most contrasting relative to other ashes in terms of both age and trace element composition (table, Fig. 2).

(2) Comparison of the composition of coeval ashes from the Kamchatkan and Magadan volcanoes suggests

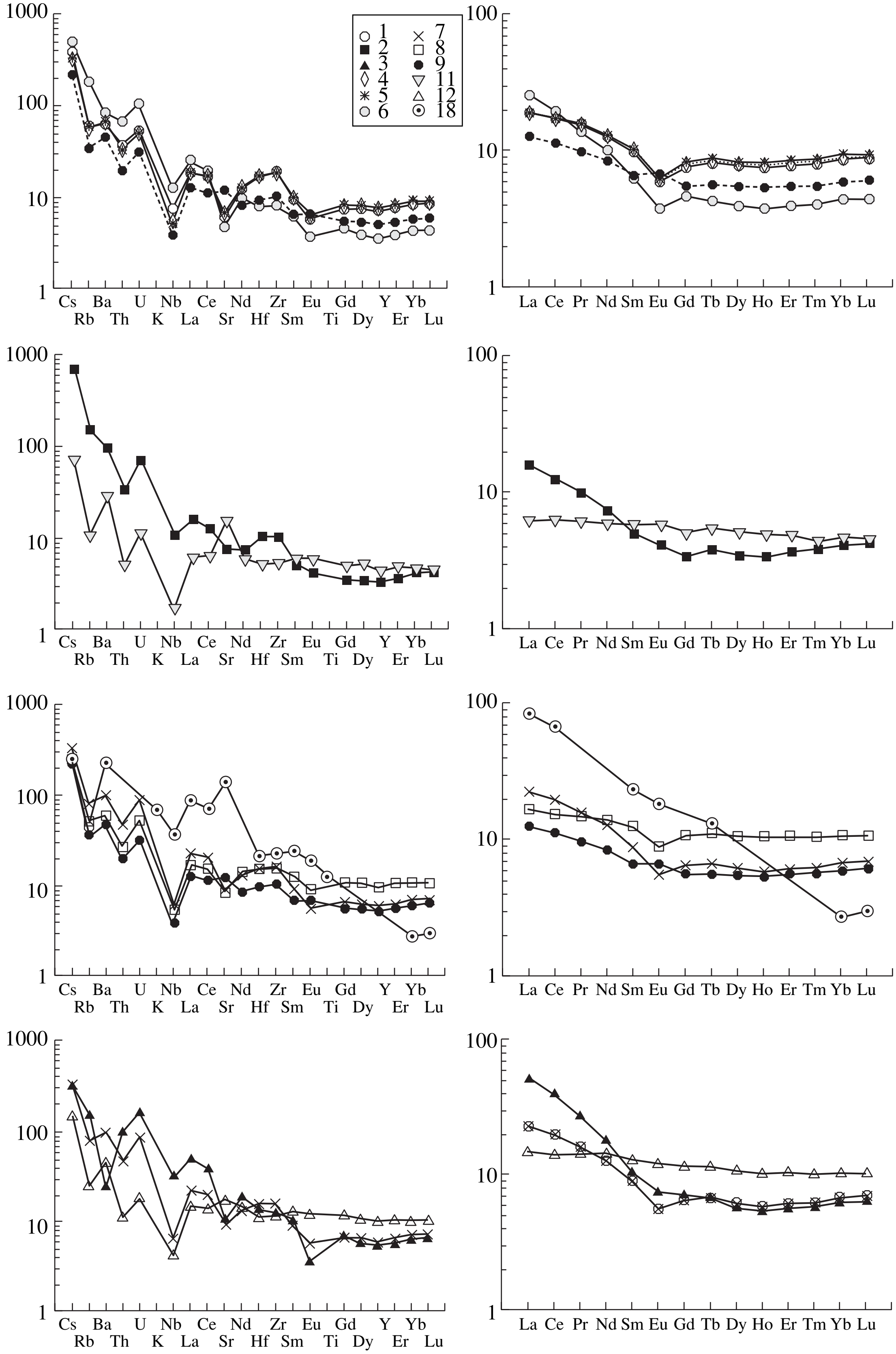

Fig. 2. PM-normalized [7] trace and REE distribution patterns. Sample numbers are as in the table.

Major components (wt %) and concentrations of trace elements (ppm) in Pleistocene–Holocene ashes and basalts of the Russian Northeast and in tephra and ashes of the Kamchatkan volcanoes

Component	1 (7.6)	2 (2.5)	3 (70.0)	4 (7.6)	5 (7.6)	6 (7.6)	7 (60–40)	8 (180–160)	9 (7.6)	10 (6.9)
SiO_2	69.05	67.35	71.73	69.54	68.72	75.30	73.75	78.39	59.01	67.21
TiO_2	0.56	0.95	0.27	0.39	0.65	0.58	0.95	0.70	0.50	0.37
Al_2O_3	13.20	12.18	12.38	13.17	14.04	12.30	15.62	14.31	18.81	14.63
Fe_2O_3	1.52	3.72	0.51	1.39	0.66	0.73	3.44	1.79	3.21	0.35
FeO	0.70	1.15	0.34	0.61	1.64	0.35			1.45	1.03
MnO	0.05	0.08	0.06	0.04	0.04	0.01	0.52	–	0.10	0.05
MgO	0.23	1.26	0.10	0.10	0.25	0.16	0.87	1.27	1.03	0.95
CaO	2.48	2.69	1.52	2.32	2.01	1.59	2.01	1.01	4.50	2.51
Na_2O	4.25	3.02	4.13	4.30	2.05	4.35	1.96	1.14	3.73	3.85
K_2O	1.62	1.98	4.42	1.72	2.83	3.55	1.86	1.84	1.11	2.60
H_2O^-	0.93	0.54	0.38	0.57	0.62	0.17	Not det.	Not det.	1.51	0.54
P_2O_5	0.09	–	0.02	0.13	0.14	0.11	Not det.	Not det.	0.10	0.27
L.O.I.	5.14	4.69	3.74	5.37	5.17	0.62	Not det.	Not det.	4.69	5.15
Total	99.79	99.61	99.60	99.66	99.78	99.85	100.98	100.45	99.75	99.51
V	24.52	93.33	4.36	12.10	11.63	15.66	45.47	32.44	100.68	138.61
Cr	3.62	20.43	2.66	1.16	0.89	3.09	6.36	3.22	11.51	229.70
Co	1.47	4.61	0.35	1.40	1.73	0.60	5.99	4.56	8.23	24.73
Ni	0.46	4.24	0.56	0.74	4.99	0.35	7.58	1.50	3.02	46.96
Rb	34.08	84.24	86.81	32.60	33.81	104.61	43.72	28.11	19.51	9.90
Sr	117.16	140.42	20.92	127.72	129.79	91.95	173.48	157.68	238.60	691.27
Y	28.91	12.74	21.08	30.27	30.36	14.21	22.82	37.29	20.10	14.42
Zr	194.20	96.85	127.27	184.50	186.45	82.68	160.73	151.83	103.81	60.84
Nb	5.00	6.86	21.56	3.62	3.44	8.63	4.14	3.51	2.57	2.17
Cs	2.88	4.93	2.31	2.32	2.40	3.70	2.28	1.70	1.57	0.40
Ba	414.47	593.68	159.84	436.22	448.28	546.82	614.51	373.58	297.47	285.55
La	12.21	9.91	32.77	12.29	12.18	16.40	14.42	10.72	8.13	7.30
Ce	28.24	19.78	64.93	28.48	28.51	31.69	32.16	24.54	18.44	16.83
Pr	3.86	2.47	7.05	3.97	4.00	3.53	4.09	3.79	2.51	2.58
Nd	15.74	8.86	23.01	16.01	16.08	12.48	15.73	17.09	10.43	11.69
Sm	3.97	1.99	4.29	4.10	4.18	2.58	3.63	5.03	2.72	3.07
Eu	0.91	0.62	0.54	0.96	0.96	0.58	0.84	1.37	1.03	1.08
Gd	4.15	1.83	3.85	4.39	4.48	2.53	3.50	5.79	2.97	3.12
Tb	0.80	0.37	0.68	0.83	0.87	0.43	0.66	1.09	0.56	0.52
Dy	5.25	2.26	3.87	5.46	5.53	2.66	4.09	7.12	3.66	3.02
Ho	1.13	0.50	0.81	1.19	1.23	0.57	0.86	1.56	0.81	0.61
Er	3.45	1.58	2.45	3.59	3.74	1.75	2.64	4.60	2.42	1.67
Tm	0.55	0.26	0.40	0.58	0.59	0.28	0.42	0.71	0.38	0.24
Yb	3.90	1.84	2.80	3.99	4.15	2.00	3.02	4.76	2.65	1.64
Lu	0.60	0.28	0.43	0.62	0.62	0.30	0.46	0.71	0.41	0.23
Hf	4.96	2.83	4.03	4.88	4.92	2.31	4.31	4.31	2.73	1.61
Ta	0.40	0.63	1.24	0.31	0.30	0.76	0.37	0.34	0.20	0.21
Pb	11.73	12.36	13.75	25.14	10.88	22.50	11.39	7.41	7.86	5.19
Th	3.35	2.96	8.94	2.97	3.00	6.17	4.10	2.31	1.75	0.57
U	1.22	1.56	3.68	1.15	1.15	2.44	1.96	1.15	0.71	0.31
Hf/Ta	12.40	4.49	3.25	15.74	16.40	3.04	11.65	12.68	13.65	7.67
Cr/Ni	7.87	4.82	4.75	1.56	0.18	8.83	0.83	2.15	3.81	4.89
Sr/Rb	3.44	1.67	0.24	3.92	3.84	0.88	3.97	5.61	12.23	69.83
Ce/Yb	7.20	10.7	23.2	7.10	6.90	15.80	10.70	5.20	6.96	10.26
Nb/Yb	1.30	3.70	7.70	0.90	0.80	4.32	1.40	0.70	0.97	1.32
Zr/Yb	49.80	52.60	45.40	46.90	41.90	41.30	53.20	31.87	39.17	28.0
Ba/Nb	82.87	86.47	7.39	120.87	130.28	63.39	148.38	106.39	115.74	160.08
ΣTr + Y	113.70	65.30	168.91	116.68	117.47	91.87	109.29	126.18	77.19	76.37
K/Ti	2.87	2.08	16.4	4.41	1.54	0.12	1.96	2.63	2.22	7.02

11 (3.5)	12 (40–30)	13 (6.0)	14 (30–20)	15 (15.5)	16 (10.0)	17 (20.0)	18 (400–200)	19 (800–500)	20 (2200–500)
51.31	63.81	52.93	54.85	57.96	49.84	63.63	46.30	49.68	44.34
1.06	0.76	0.74	0.93	0.49	1.11	0.72	2.36	2.09	2.13
15.97	15.77	18.56	21.40	19.46	18.61	17.08	14.90	15.59	12.43
6.70	2.38	3.87	4.60	3.56	5.90	5.13	8.80	3.94	4.74
5.03	3.26	3.02	1.30	2.56	4.39	0.72	2.17	7.09	6.73
0.19	0.22	0.18	0.12	0.15	0.19	0.20	0.12	0.12	0.10
5.06	1.43	1.17	1.47	1.96	3.70	1.58	8.26	7.20	14.62
8.96	3.53	4.73	3.11	6.92	8.40	4.12	8.22	6.98	7.45
2.85	4.48	3.40	3.24	3.40	3.37	4.94	4.76	3.64	4.57
0.55	1.13	0.75	1.80	0.77	0.69	1.08	2.22	1.85	2.27
0.28	0.37	3.74	0.37	0.25	0.56	0.20	–	0.79	0.06
0.17	0.29	0.25	0.25	0.13	0.28	0.25	1.34	0.50	0.60
1.49	2.22	6.17	6.42	2.42	2.80	–	0.85	0.41	0.43
99.62	99.65	99.52	99.86	99.73	99.86	99.65	100.23	100.56	100.43
373.02	54.14	138.19	116.16	126.0	338.93	62.25	–	–	–
6.97	1.56	6.27	15.15	5.57	9.56	3.63	340	170	540
26.78	7.34	14.95	11.66	11.57	27.27	6.39	49.0	43.0	73
12.61	3.89	3.58	9.69	6.13	7.06	2.39	170	890	1100
6.02	14.53	10.71	41.98	10.50	6.30	13.38	24.2	16.0	22.0
297.24	334.69	243.66	306.43	469.38	351.63	295.57	2600	500	950
16.72	39.55	35.24	46.48	12.58	27.59	38.0	–	19.3	–
51.50	115.25	118.41	498.68	75.36	90.62	48.11	220	185	200
1.09	2.82	2.44	14.36	1.71	2.93	2.53	24.0	45.0	56.0
0.52	1.09	1.03	2.88	0.49	0.48	1.05	–	0.19	–
174.49	301.32	231.69	1106.91	180.41	163.20	288.74	1400	230	360
3.92	9.72	9.75	34.25	5.54	6.88	8.94	54	20.4	36.0
9.99	23.19	26.90	82.85	12.35	17.81	28.93	110	36.2	60
1.57	3.72	4.05	10.26	1.76	2.73	3.76	–	4.58	–
7.17	18.13	18.77	40.83	7.72	12.59	17.31	–	22.8	–
2.33	5.31	5.25	8.93	2.02	3.78	5.31	9.7	5.54	7.0
0.89	1.85	1.60	2.28	0.75	1.37	1.81	2.8	1.83	2.1
2.72	6.28	6.01	8.62	2.08	4.54	6.35	–	5.59	–
0.53	1.14	1.07	1.50	0.38	0.82	1.14	1.3	0.81	1.0
3.37	7.28	6.73	8.88	2.41	5.34	7.14	–	4.19	–
0.74	1.55	1.44	1.86	0.51	1.14	1.50	–	0.75	–
2.10	4.59	4.21	5.42	1.51	3.31	4.29	–	1.86	–
0.30	0.69	0.61	0.84	0.23	0.49	0.62	–	0.29	–
2.08	4.61	4.25	5.79	1.60	3.32	4.11	1.2	1.48	1.5
0.30	0.69	0.64	0.86	0.23	0.50	0.59	0.20	0.22	0.23
1.41	3.14	3.23	11.41	1.77	2.30	1.70	5.9	4.54	5.5
0.11	0.21	0.72	0.92	0.22	0.21	0.15	2.4	2.1	4.3
3.98	9.23	8.31	23.73	8.76	4.02	7.76	–	–	–
0.44	1.01	1.10	7.23	0.44	0.59	0.60	–	2.96	–
0.25	0.42	0.47	2.54	0.26	0.33	0.17	–	1.08	–
12.82	14.95	4.49	12.4	8.05	10.95	11.33	2.45	2.16	1.28
0.55	0.26	1.75	1.56	0.91	1.35	1.52	2.00	1.91	0.49
49.38	23.03	22.75	7.30	44.70	55.81	22.09	107.41	31.25	43.18
4.08	5.03	6.33	14.31	7.72	5.36	7.08	91.70	24.46	40.00
0.52	0.61	0.57	2.48	1.07	0.88	0.62	20.0	31.03	37.3
47.24	40.87	48.53	34.70	44.08	30.93	19.02	9.66	4.11	6.00
160.10	106.85	94.95	77.10	105.50	55.69	114.13	58.33	5.11	6.43
38.0	128.30	126.50	259.6	51.68	64.61	129.80	179.20	106.72	107.18
0.52	1.49	1.01	1.94	1.57	0.62	1.50	0.94	0.88	1.06

Note: Numbers in parentheses denote age, ka. Ashes from exposures and boreholes from the Russian Northeast: (1) Levaya Palatka, (2) Port Magadan, (3) Uptar deposit, (4) Lake Chistoe, (5) Lake Grand, (6) Levyi Divnyi; Core from Lake El'gygytgyn: (7) upper horizon, (8) lower horizon; Ashes from the Kamchatkan volcanoes: (9) Caldera of Lake Kuril'skoe (volume of ejecta, $V = 140–170$ km^3), (10) Khangar ($V = 14–16$ km^3), (11) Avacha ($V \sim 4$ km^3), (12) Ksudach, (13) Ksudahc ($V = 9–11$ km^3), (14) Gorelyi; (15) Ksudach; (16) Zhupanovskii; (17) Ksudach; basaltic volcanoes of the Russian Northeast: (18) Balagan-Tass (vent), (19) Aluchinskii, (20) Zhokhov Is.

Major elements were analyzed at the Far East Geological Institute, Vladivostok (L.I. Alekseeva and L.V. Nedhaskovskaya, analysts); trace elements were analyzed using the ICP-MS method at the Vinogradov Institute of Geochemistry, Irkutsk (G.P. Sandimirova, analyst); ages of ashes and tephra were determined by the radiocarbon (^{14}C) method [3, 4]; absolute ages of basalts were determined by K–Ar and Ar–Ar methods [5].

the following conclusion. The Magadan ashes are closest to the tephra of Lake Kuril'skoe Caldera, but they slightly differ in major and trace element composition. The ashes from Grand and El'gygytgyn lakes are closest to the ashes of the Lake Kuril'skoe Caldera, but they differ in age (7.6 ka Ma for Grand and Kuril'skoe lakes; 40–60 and 160–180 Ma for Lake El'gygytgyn) and in the trace element pattern.

The similarity and differences between compositions of the Magadan and Kamchatkan ashes are well illustrated in spidergrams and indicator ratios (e.g., Sr/Nb, Sr/Rb, and others). These features are observed in ash interbeds of both similar and different ages (Fig. 2).

3. Major and trace element data indicate that tephra and ashes of basaltic volcanoes of the Russian Northeast (Zhokhov Island, Aluchinskii, and others) could not be sources of these ash interbeds (Fig. 2).

4. The compositional diversity of ashes in the Russian Northeast can be explained by mixing of different (in composition and age) ashes in the course of their redeposition as ash interbeds. Interesting data were obtained during dating of ashes from the Lake El'gygytgyn Caldera. The study of microfauna [6] showed that the core from this lake contains not only late Pleistocene diatomaceous algae, but also valves of the older (Miocene) diatoms. Hence, the redeposition was accompanied by mixing of ashes of different (in composition and age) volcanic eruptions, suggesting different sources (eruption centers).

5. Dacite and rhyolite ashes of the older (70, 40–60, 160–180 ka) ashes of the Russian Northeast have no analogues in the reference collections of the Kamchatkan ashes analyzed in this work. The compositional features of these ashes (REE, trace, and petrogeochemical characteristics) suggest that their origin is related to local eruption centers, which have not yet been found.

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