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Identification of a widespread Kamchatkan tephra: A middle Pleistocene tie-point between Arctic and Pacific paleoclimatic records

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[1] Very few age controls exist for Quaternary deposits over the vast territory of the East Russian Arctic, which hampers dating of major environmental changes in this area and prevents their correlation to climatic changes in the Arctic and Pacific marine domains. We report a newly identified ~177 ka old Rauchua tephra, which has been dispersed over an area of >1,500,000 km^2 and directly links terrestrial paleoenvironmental archives from Arctic Siberia with marine cores in the northwest Pacific, thus permitting their synchronization and dating. The Rauchua tephra can help to identify deposits formed in terrestrial and marine environments during the oxygen isotope stage 6.5 warming event. Chemical composition of volcanic glass from the Rauchua tephra points to its island-arc origin, while its spatial distribution singles out the Kamchatka volcanic arc as a source. The Rauchua tephra represents a previously unknown, large (magnitude >6.5) explosive eruption from the Kamchatka volcanic arc. **Citation:** Ponomareva, V., M. Portnyagin, A. Derkachev, O. Juschus, D. Garbe-Schönberg, and D. Nürnberg (2013), Identification of a widespread Kamchatkan tephra: A middle Pleistocene tie-point between Arctic and Pacific paleoclimatic records, *Geophys. Res. Lett.*, *40*, 3538–3543, doi:10.1002/grl.50645.

1. Introduction

[2] Establishing precise correlations between distant paleoenvironmental archives is important for resolving the spatial and temporal complexities of past climatic changes. Tephra layers from large explosive eruptions have proved to work as excellent isochrones directly linking marine and terrestrial depositional successions and allowing an evaluation of the synchronicity of abrupt climate changes [e.g., *Davies et al.*, 2008]. Once dated, a tephra layer provides age control for all other sections where it has been geochemically identified. Some tephras have been recently found at distances of more than 8000 km from their source [*Jensen et al.*, 2012], which attests to the potential of tephra for correlation of distant sites. In addition, tephra correlations permit estimates of tephra volumes, which in turn may serve as a basis for evaluating magma output and volcanic gas flux through time as well as contribute to hazard assessment.

[3] Numerous distal tephra layers have been reported over northeast Asia and surrounding seas (Figure 1) both in terrestrial and marine environments [*Kotov*, 1998; *Nürnberg and Tiedemann*, 2004; *Juschus et al.*, 2007]. To date, however, only one tephra associated with the Kurile Lake caldera-forming eruption ~8.4 cal ka BP has been reliably correlated between the source in South Kamchatka, cores in the Okhotsk Sea, and distal sites on the Asian mainland (Figure 1) [*Ponomareva et al.*, 2004; *Derkachev et al.*, 2012]. Dispersal areas and sources for many other distal tephras are not yet constrained which hampers their usage for dating and correlation of distant paleoclimatic archives. This paper reports new data on the geochemical correlation of a middle Pleistocene tephra from Kamchatka over an area of >1,500,000 km^2 and discusses its potential as a marker for the marine oxygen isotope stage (MIS) 6.5 warming event in northeast Asia and adjacent seas. Wide dispersal of this tephra suggests an earlier unknown explosive eruption from the Kamchatka volcanic arc, which may rank within the Earth's largest eruptions.

2. Sample Localities for the Rauchua Marker Tephra

[4] A volcanic ash of unique composition, which we label the Rauchua tephra, was identified in two terrestrial sites in the East Russian Arctic and two marine cores in the northwest Pacific (Figure 1). The sites are: (1) the Rauchua outcrop on the Eastern Siberian Sea coast, (2) core Lz1024 in the El'gygytgyn Lake (Chukotka); (3) core SO201-2-81KL (Bering Sea), and (4) core SO201-2-40KL (northwest Pacific) (Table S1 in the supporting information).

[5] 1. The Rauchua outcrop (Figure 2) was originally described and sampled by *Kotov* [1998]. The ~6 km long coastal bluff exposes a carbon-rich permafrost sequence, typical for the Arctic Siberia and composed of massive silts interlayered with lake deposits and peats [*Schirrmeister et al.*, 2011]. The sequence records two cold climate phases with the formation of silts, and three warmer phases with the formation of thermokarst lakes due to permafrost thaw [*Kotov*, 1998]. A 1–10 cm thick layer of white fine ash was described in many subsections along the outcrop, either

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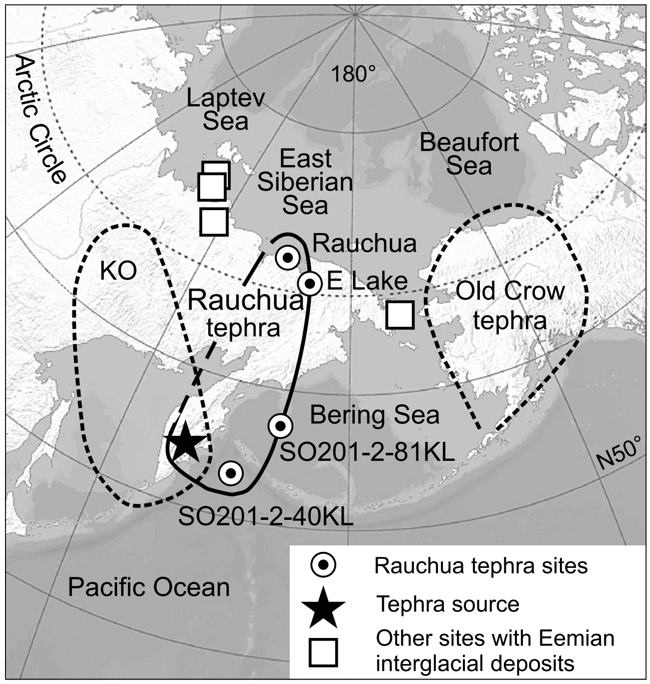

Figure 1. Location of the Rauchua tephra sites and its minimum outline (solid line); with Old Crow (~124 ka) [*Preece et al.*, 2011] and Kurile Lake (KO, ~8.4 ka) [*Ponomareva et al.*, 2004] tephras outlines (dashed) for comparison. Karymsky volcanic center is shown with the star. Some other sites with the MIS 5e (Eemian) interglacial deposits according to *Brigham-Grette et al.* [2001], *Kaplina* [2011], and *Schirrmeister et al.* [2011]. Long axis of the Rauchua tephra outline is ~1800 km.

within the middle peat layer or within the lower silt, 30–50 cm below the peat (Figure 2, subsections 1 and 2, respectively). The analyzed sample "Rauchua" comes from below the peat.

[6] Radiocarbon dates on twigs and bulk peats from the Rauchua sequence split into two populations: (1) three dates from the upper lacustrine deposits are early Holocene [*Kotov*, 1998], and (2) 10 dates from all the other layers are infinite (beyond the range of ^{14}C method, ~50 ka) [*Anderson and Lozhkin*, 2002]. Pollen data for the middle lacustrine package (Figure 2) point to a warmer-than-present climate [*Anderson and Lozhkin*, 2002]. The whole sequence, except for its Holocene cover, has been related to the late Pleistocene [*Kotov*, 1998], more precisely, to the first half of the Karginsky interstadial [*Anderson and Lozhkin*, 2002] traditionally assigned to MIS 3 [*Astakhov*, 2013].

[7] 2. El'gygytgyn Lake is located ~330 km southeast from the Rauchua site (Figure 1). It has been cored several times since 1998 with a major International Continental Scientific Drilling Program core taken in 2009 [*Melles et al.*, 2012]. The pilot cores were integrated into the ICDP Site 5011 record, which spans the past 3.6 million years. The age-depth model for the composite site was derived from the systematic tuning of various proxies to the Northern hemisphere insolation and

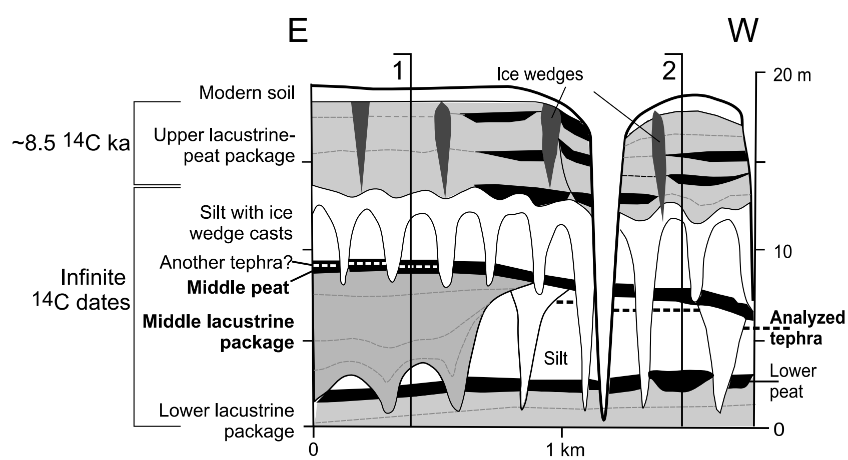

Figure 2. Eastern part of the Rauchua outcrop (modified from *Kotov* [1998]). The outcrop exhibits two massive silt units with ice wedge casts, three packages of lacustrine deposits interlayered or capped with peat, and modern soil. Tephra is shown with black (in silt) or white (in peat) dashed line. Numbers 1 and 2 show position of typical subsections discussed in the text.

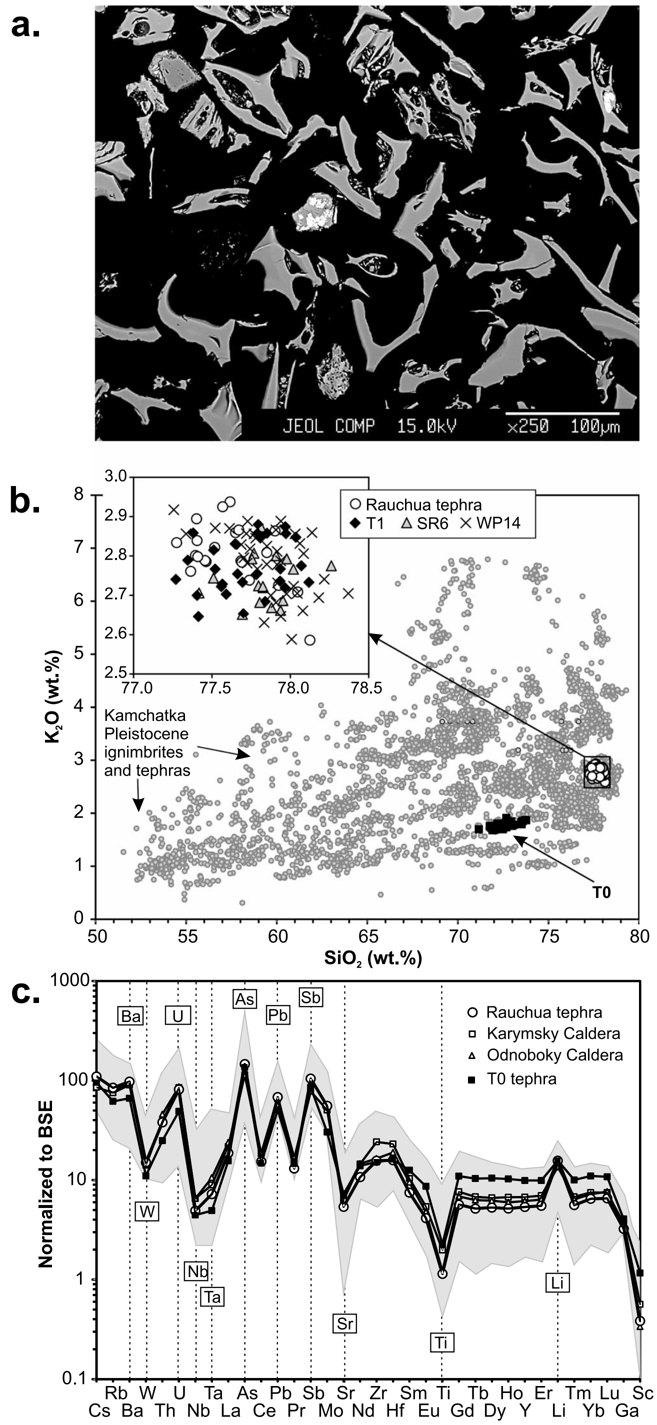

Figure 3. Composition of Rauchua tephra: (a) Backscattered electron image of Rauchua tephra (Rauchua outcrop); (b) K_2O-SiO_2 plot showing composition of Rauchua and T0 tephra glass against that of Pleistocene Kamchatka ignimbrites and tephras analyzed thus far; and (c) plot of trace element composition of Rauchua and T0 tephras normalized to Bulk Silicate Earth [*McDonough and Sun*, 1995. Composition of rhyolites from Karymsky and Odnoboky calderas and field of all the Kamchatkan tephras (gray shade) is provided for comparison.

the marine oxygen isotope stack [*Nowaczyk et al*., 2013]. Eight visible tephra layers have been found in the composite core [*Nowaczyk et al*., 2013]. Sample Lz1024-EL2, obtained from a pilot core in 2003 (Table S1), comes from the second layer from the top [*Juschus et al*., 2007]. The age of this tephra (labeled T1) was estimated at ~177 ka [*Nowaczyk et al*., 2013], and it falls into the MIS 6.5 warm phase [*Frank et al*., 2012].

[8] 3. In core SO201-2-81KL (Bering Sea) (Figure 1), a layer of fine ash coded SR6 occurs at a depth of 861.5–862.5 cm [*Dullo et al*., 2009]. Correlation of this core to the nearby core SO201-2-85KL with the established age-depth model [*Dullo et al*., 2009; *Riethdorf et al*., 2012] allows us to infer that the SR6 tephra was deposited prior to 160 ka BP.

Table 1. Average Composition of the Rauchua Glass[a]

Element	Units	N Points	Concentration	1 SD
SiO_2	wt %	103	77.78	0.24
TiO_2	wt %	103	0.23	0.07
Al_2O_3	wt %	103	12.41	0.11
FeO	wt %	103	1.15	0.12
MnO	wt %	103	0.06	0.05
MgO	wt %	103	0.20	0.02
CaO	wt %	103	1.19	0.03
Na_2O	wt %	103	4.02	0.16
K_2O	wt %	103	2.78	0.08
P_2O_5	wt %	103	0.02	0.02
F	wt %	49	0.02	0.04
SO_3	wt %	103	0.01	0.01
Cl	wt %	103	0.16	0.01
Total	wt %		**100.00**	
Li	ppm	31	24.2	3.0
Sc	ppm	31	6.4	0.5
Ti	ppm	31	1375	59
V	ppm	31	8.3	3.7
Cu	ppm	31	12.3	9.7
Zn	ppm	31	32.1	6.3
Ga	ppm	31	12.6	0.9
As	ppm	20	7.5	2.1
Rb	ppm	31	48.8	4.2
Sr	ppm	31	105	6
Y	ppm	31	23.6	2.3
Zr	ppm	31	166	16
Nb	ppm	31	3.23	0.23
Mo	ppm	20	2.59	0.34
Sb	ppm	20	0.54	0.08
Cs	ppm	20	2.19	0.26
Ba	ppm	31	618	52
La	ppm	31	12.1	1.0
Ce	ppm	31	24.9	2.2
Pr	ppm	31	3.21	0.20
Nd	ppm	31	13.3	0.8
Sm	ppm	31	3.06	0.25
Eu	ppm	31	0.63	0.05
Gd	ppm	31	3.04	0.34
Tb	ppm	31	0.52	0.05
Dy	ppm	31	3.56	0.38
Ho	ppm	31	0.79	0.07
Er	ppm	31	2.51	0.25
Tm	ppm	31	0.38	0.05
Yb	ppm	31	2.89	0.31
Lu	ppm	31	0.46	0.05
Hf	ppm	31	4.45	0.51
Ta	ppm	31	0.28	0.03
W	ppm	20	0.44	0.17
Pb	ppm	31	9.66	0.91
Th	ppm	31	3.08	0.31
U	ppm	31	1.55	0.15

[a]The composition represents an average from all analyses of single-glass shards obtained at four localities. Major elements were analyzed by electron microprobe, trace elements by LA-ICP-MS. The analytical procedure is described in Text S1 and Table S2.

[9] 4. In core SO201-2-40KL (northwest Pacific), a ~10 cm thick tephra coded WP14 occurs at a depth of 704.5–714.5 cm and is composed of fine to medium sand (Figure 1; Table S1) [*Dullo et al*., 2009].

3. Rauchua Glass Composition

[10] All samples are dominated by colorless volcanic glass with typical bubble-wall appearance and fluidal texture (Figure 3a). Geochemical characterization of single-glass shards was done with the help of high-precision electron microprobe and laser-ablation inductively couple mass spectrometry (LA-ICP-MS) under conditions described in Text S1 and Table S2. The chemical compositions of volcanic glass obtained at four localities are given in Tables S3 and S4.

[11] Glasses from all the four sites are indistinguishable or very similar in terms of major and trace element composition (Figures 3b and 3c) and likely originate from the same volcanic eruption. The glasses have med-K rhyolite near-homogeneous composition ($SiO_2 = 77.8 \pm 0.2$ wt %, $K_2O = 2.78 \pm 0.08$ wt %, 1 SD, N = 103) with a very narrow range of all other major elements, Cl (0.16 ± 0.01 wt %) and trace elements (Table 1; Figures 3b and 3c). Coefficients of similarity [*Borchardt* et al., 1971] for Rauchua glass and those from three other localities calculated for 44 elements are 0.90–0.91, and those for seven major elements are 0.94–0.96, which confirms the likeness of all the glasses. Formal *t*-test for the case of two-tail distribution and unequal variances (Microsoft Excel) also confirms close similarity of the glasses (Tables S3 and S4). The deviations from equality are rather random and likely reflect occasional and unaccounted for analytical uncertainties or specific conditions of deposition (e.g., high Cu in SR6 sample resulting from contamination by sulfide precipitates on glass surfaces). Composition of the Rauchua tephra is distinctly different from that of the younger T0 tephra in the El'gygytgyn Lake core (Figures 3b and 3c; Table S5) [*Juschus et al*., 2007].

[12] Trace elements in the Rauchua glass normalized to the composition of the Bulk Silicate Earth [*McDonough and Sun*, 1995] exhibit a zigzag pattern (Figure 3c) with strong relative enrichment of large ion lithophile elements (Cs, Rb, and Ba), U, As, Sb, Li, and Pb relative to similarly incompatible rare-earth and high-field strength elements (Ta, Nb, W, Zr, and Hf) and low $[Nb(Ta)/La]_N < 1$ and $[Nb/Y]_N \sim 1$ that suggest an island-arc origin of the Rauchua tephra [e.g., *Pearce*, 1982; *Noll et al*., 1996].

4. Rauchua Tephra: Age, Dispersal, Source, and Eruption Magnitude

[13] Based on close resemblance of major and trace element composition of glass from Rauchua, T1, SR6, and WP14 tephras, we propose that they represent the same tephra. The age of ~177 ka obtained for the Rauchua tephra in the El'gygytgyn Lake core [*Nowaczyk et al*., 2013] can thus be applied to all other sites where this tephra is present. The Rauchua tephra has the greatest thickness (~10 cm) and contains the coarsest material (medium sand) in core SO201-2-40KL (Figure 1). Dispersal pattern for the Rauchua tephra, thus, points at Kamchatka rather than the Aleutian arc as a source (Figure 1).

[14] The Kamchatka volcanic arc represents the northwest segment of the Pacific Ring of Fire and is highly explosive with the largest number of calderas per unit of arc's length in the world [*Hughes and Mahood*, 2008] and with the dense cluster of nested calderas in the Karymsky volcanic center. A few dated ignimbrites from this area cover a range between ~1300 and 8.7 ka BP [*Braitseva et al*., 1995; *Bindeman et al*., 2010]. There is no exact match for the Rauchua tephra within the age and geochemical data available for this area, however, as yet many local ignimbrites have not been dated or geochemically characterized [e.g., *Leonov and Grib*, 2004]. Geochemical characteristics for the Rauchua tephra

are similar to rhyolites from the Karymsky volcanic center which is its most probable source (Figure 3c).

[15] A rough estimate of a minimum volume (Vmin) for the Rauchua tephra is based on a single 1 cm isopach [*Legros*, 2000] enclosing all of the studied sites (Figure 1) and gives Vmin of 49.82 km^3. The magnitude (M) of the Rauchua eruption can be estimated at >6.5 [method by *Pyle*, 2000; assuming pumice density of 0.641 g/cm^3]. The Rauchua tephra thus records a previously unknown $M > 6.5$ eruption from a source likely hidden under nested calderas in the Karymsky volcanic center in eastern Kamchatka. An average tephra thickness of 5 cm observed along the Arctic coast suggests that volume and magnitude estimates for this eruption may increase dramatically when the outermost limits of the Rauchua tephra dispersal are defined.

[16] The Rauchua tephra is one of only eight tephras that covered the Far East Russian Arctic with a visible layer during the last 3.6 Ma [*Nowaczyk et al*., 2013]. This indicates that the Rauchua eruption was a relatively rare and significant volcanic event likely comparable in size to the Earth's largest eruptions, e.g., the Millennium eruption of Changbaishan volcano [*Horn and Schmincke*, 2000] or the Kurile Lake caldera-forming eruption (Figure 1) [*Ponomareva et al*., 2004], and might have had a substantial climatic impact. Remarkably, the Rauchua tephra, as well as some other large tephras (Figure 1), was dispersed across the westerly polar jet stream, which indicates that its pattern could have been different from the present jet stream.

5. Implications for Geochronology and Paleoclimate

[17] A few continuous records of late to middle Pleistocene climate change are available from northeast Asia and adjacent seas [e.g., *Nürnberg and Tiedemann*, 2004; *Max et al*., 2012; *Riethdorf et al*., 2012]. These records exhibit alternating warm and cool phases consistent with other paleoclimatic records from the Northern hemisphere [*Melles et al*., 2012]. It is still not clear, however, which of these phases have caused the most prominent changes in the landscape over the vast territory of the northeast Siberia, inducing permafrost melting or accumulation of massive silts. In the absence of reliable dating tools, the age of terrestrial deposits beyond the limits of radiocarbon dating remains very uncertain [*Astakhov*, 2013].

[18] We propose the Rauchua tephra as a robust marker, which permits the identification of the middle Pleistocene deposits in northeast Asia and adjacent seas, and more specifically, pinpoints the deposits accumulated during the MIS 6.5 warming event. This event was characterized by abrupt changes from glacial to interglacial-type conditions and caused prominent effects over a large area from the Mediterranean to China (strong Mediterranean rainfalls, a sapropel event (S6) in the eastern Mediterranean Sea, changes in monsoon patterns, etc.) [e.g., *Margari et al*., 2010; *Penaud et al*. 2009, and references herein]. It is plausible that this event has left significant, but not yet recognized traces in northeast Asia as well. The Rauchua tephra, thus, will allow an assessment of the regional development of the 6.5 warming event.

[19] The whole Rauchua sequence was earlier assigned to late Pleistocene [*Kotov*, 1998; *Lozhkin and Anderson*, 2002] as well as many similar permafrost deposits along the Siberian Arctic coastline [*Schirrmeister et al*., 2011]. Our findings show that these typical carbon-rich permafrost deposits started to form in the middle Pleistocene, well prior to MIS 6.5. No glacial till or marine deposits are present in the Rauchua outcrop indicating that this area has not been glaciated or submerged during the last >177 ka. The middle lacustrine-peat package (Figure 2) is likely to record the latest pre-Holocene permafrost thaw at this site with the formation of thermokarst lakes and accumulation of the lacustrine-peat deposits. The analyzed Rauchua tephra lies only 30–50 cm below the peat, which suggests that these "warm" Karginsky [*Anderson and Lozhkin*, 2002] sediments formed during MIS 5e (Eemian) interglacial (116–130 ka BP [*Melles et al*., 2012]) rather than during MIS 3 (55–24 cal ka BP). This conclusion is consistent with the results of a recent redating of the Karginsky interstadial in western Siberia [*Astakhov*, 2013]. The tephra described by *Kotov* [1998] within the middle peat layer should be significantly younger and likely represents another tephra, which still needs to be analyzed.

[20] The Rauchua tephra ensures direct comparison of the marine paleoenvironmental archives in the Bering Sea and northwest Pacific with the well-studied record of the El'gygytgyn lake [*Melles et al*., 2012], which may help to test the synchronicity of the MIS 6.5 warming event in marine and terrestrial environments. The presence of the Rauchua tephra as a visible layer along the Arctic coast and in the northwest Pacific indicates that it may be found as cryptotephra (scattered volcanic glass) yet farther north and east, and thus help to recognize MIS 6.5 sediments in the Arctic and Pacific marine cores and, possibly, even in the North Atlantic, thus permitting a large scale interregional correlations of paleoclimatic records. This study highlights a significant potential of using this and other tephra layers in the western Beringia for precise correlations of distant records.

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