

Distal tephrochronology in volcanic regions: Challenges and insights from Kamchatkan lake sediments

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- 1 Distal tephrochronology in volcanic regions: challenges and insights from Kamchatkan lake
- 2 sediments
- 3 Gill Plunkett¹*, Sarah E. Coulter¹, Vera V. Ponomareva², Maarten Blaauw¹, Andrea Klimaschewski¹ &
- 4 Dan Hammarlund³
- 5
- ⁶ ¹School of Geography, Archaeology and Palaeoecology, Queen's University Belfast, Belfast, Northern
- 7 Ireland, UK
- 8 ²Institute of Volcanology and Seismology, Petropavlovsk-Kamchatsky, Russia
- ³Quaternary Sciences, Department of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund,
- 10 Sweden
- 11 *Corresponding author: <u>g.plunkett@qub.ac.uk</u>
- 12

14 Abstract

15 Kamchatka is one of the world's most active volcanic regions and has hosted many explosive 16 eruptions during the Holocene. These eruptions had the potential to disperse tephra over wide 17 areas, forming time-synchronous markers wherever those tephras are found. Recent research in 18 Kamchatka has begun to focus on the geochemical analysis of individual glass shards in order to 19 characterise tephra layers. We have applied this approach to the study of visible tephras from three 20 lakes - one in central and two in northern Kamchatka - with the aim of identifying key tephras and 21 potential issues in the application of distal (>100 km from an active volcano) tephra in volcanically 22 complex regions. In total, 23 tephras from 22 tephra beds have been geochemically analysed, 23 representing products from at least four volcanic systems in Kamchatka. We demonstrate that distal 24 lake sediments in the region can yield reliable tephrostratigraphies, capturing tephra from eruptions 25 that have the greatest potential to disperse volcanic ash beyond the region. We draw attention to 26 issues relating to correlating and distinguishing key marker horizons from the highly active Shiveluch 27 Volcano, namely the need to ensure inter-lab comparability of geochemical data and good 28 chronological control of the proximal and distal tephras. Importantly, we have also extended the 29 known distribution of two key tephra isochrons from the Ksudach volcano. Our work contributes 30 valuable glass geochemical on data several key marker beds that will facilitate future tephra and 31 palaeoenvironmental research within and beyond Kamchatka.

32

33 Keywords: distal tephra, tephrochronology, age-modelling, Kamchatka, Holocene

34

36 1.0 Introduction

37 Tephrochronology is a well-established technique for reconstructing volcanic histories and dating 38 past environmental change. Proximal tephrochronology in areas close to volcanic sources has 39 traditionally focused on characterising the morphology, whole rock geochemistry and mineralogy of 40 visible tephra beds, and mapping their extent (e.g. Thorarinsson, 1967; Braitseva et al., 1997). 41 Increasingly, characterisation of the glass component is becoming standard practice in volcanic 42 regions (e.g. Larsen, 1981; Gehrels et al., 2006; Fontijn et al., 2014), opening up opportunities to 43 extend the reach of tephrochronology well beyond the confines of the immediate tephra fallout 44 zone. In more distal locations (100s-1000s km), visible or microscopic tephra horizons comprise ash 45 beds that cannot usually be identified reliably by their petrological or morphological features but 46 instead rely on the geochemical characterisation of the glass, the tephra component that is most 47 widely dispersed. Although applied principally as a dating method, distal tephrochronology also enables the extent of volcanic ash dispersal and the possible environmental, economic and societal 48 49 impact of given eruptions to be assessed (Lane et al., 2013; Jensen et al., 2014; Sun et al., 2014). The 50 distal tephra record is essentially biased towards eruptions that were sufficiently powerful to 51 disperse ash over long distances, but can nevertheless capture events that have not been 52 documented or preserved in the proximal record (de Fontaine et al., 2007; Payne et al., 2008).

53

This paper describes the analysis of distal tephras in three lakes in Kamchatka (western Beringia) as an aid to dating the lakes' Holocene sediment sequences and as a means of assessing the value and challenges of integrating distal and proximal tephra records in a highly active volcanic region. A detailed tephrostratigraphical framework for Kamchatka has previously been established on the basis of extensive visible tephra layers, all of which derive from Kamchatkan volcanic systems (e.g. Braitseva et al., 1992; 1997; Ponomareva et al., 2007). Visible Kamchatkan tephra beds have aided the dating of palaeoenvironmental change on the Peninsula (e.g. Savoskul & Zech, 1997; Bäumler &

61 Zech, 2000; Dirksen et al., 2013) and centimetre-thick ash beds have been identified in sedimentary 62 sequences from the Sea of Okhotsk (Gorbarenko et al., 2002; Derkachev et al., 2012), the Asian 63 mainland (Melekestsev et al., 1991; Ponomareva et al., 2013b), the Kuril Islands to the south of 64 Kamchatka (Hasegawa et al., 2011; Kyle et al., 2011), the western Aleutian islands (Kyle et al., 2011), 65 the Bering Sea (Ponomareva et al., 2013a; in press) and the NW Pacific Ocean (Cao et al., 1995). The 66 first comprehensive attempt to characterise glass chemistries from major Holocene marker beds was 67 published by Kyle et al. (2011). An extensive programme of electron probe microanalysis (EPMA) of 68 88 proximal Late Pleistocene and Holocene tephras from Shiveluch Volcano, northern Kamchatka, 69 one of the region's most active volcanoes, has recently enabled the successful correlation of 70 previously unattributed distal tephras from a variety of terrestrial and marine locations in and 71 around Kamchatka (Ponomareva et al., in press).

72

73 Previous attempts to use tephrochronology to date lake sediments in volcanic regions have met with 74 varying success. Significant downward movement of tephra through soft lake sediment has been 75 observed in North American lakes, whereby tephra sank by as much as 1 m below the contemporary 76 sediment surface through density settling and in some instances formed continuous secondary 77 horizons that could be mistaken for primary ashfall beds (Anderson et al., 1984; Beierle & Bond, 78 2013). Dirksen et al. (2011) found fewer tephras represented in lake sequences than in adjacent 79 terrestrial sediments in north-central Kamchatka and concluded that the lacustrine environment 80 provided less favourable preservation conditions than onshore sites. Here too, there was evidence 81 for downward penetration of tephras as a result of density settling, although this was accompanied 82 by an incoherent tephrostratigraphy. In other volcanic regions, however, robust tephrostratigraphies 83 have been recorded in lake systems (e.g. Eden & Frogatt, 1996; Newton et al., 2005; Wulf et al., 84 2008). Spatial patchiness was observed in tephra distribution in multiple sections from Svínavatn Lake, Iceland, likely reflecting synoptic weather patterns and their impact on the lake system during 85 86 the eruptions (Boygle, 1999) and indicating that a single lake core might not fully capture a complete

tephrostratigraphy for a region. In Paradox Lake, Alaska, located close to several volcanic sources,
considerably more tephra horizons were identified in the lake sediment than in terrestrial profiles in
the area (de Fontaine et al., 2007). In this instance, the authors conclude that the higher frequency
record owed much to the suitability of the lake basin for tephra deposition and preservation.

91

92 We examine tephra records from three lakes in central and northern Kamchatka located 160-300 km 93 from Shiveluch Volcano. Ash from several major Holocene eruptions has reached central Kamchatka, mainly from volcanic systems to the south, including Ksudach, Opala, and Khangar, although a 94 95 number of Shiveluch deposits have also been identified (Fig. 1; Pevzner, 2011). The northernmost site from which a detailed, geochemically-supported tephrostratigraphy is published is Uka Bog 96 97 (57°49'N, 162°10' E), where nine tephras from Shiveluch, Ksudach, Khangar and Bezymianny were 98 identified (Dirksen et al., 2011; Kyle et al., 2011). The main events represented in the vicinity of the 99 sampling sites considered in this paper are described below. In addition, there are tephras present in 100 both areas from less well-studied eruptions, but their glass compositions have not been determined.

101

102 In our study in central and northern Kamchatka, visible tephra beds form the basis for site

103 tephrostratigraphies, most of which we geochemically characterise using EPMA. Using geochemical

104 comparisons, ¹⁴C dating and age-modelling, we evaluate the potential and limitations of applying

105 distal tephrochronology in this volcanically complex area.

106

107 **1.1** Principle Holocene tephras in the central and northern Kamchatka

108 Ksudach volcano is a shield-like stratovolcano in southern Kamchatka that features several

109 overlapping calderas formed by a series of major eruptions since the end of the Last Glacial period.

110 Two Ksudach eruptions are known in the early mid-Holocene (Braitseva et al., 1992; 1997; Volynets

111 et al., 1999). The earlier and smaller event, KS₃, erupted a tephra with dacitic glass at 6386±36 BP 112 (7420-7255 cal BP) that has been identified only to the immediate west of the volcano (Zaretskaya et 113 al. 2007; Kyle et al., 2011). The KS₂ event produced an ash with a rhyolitic to andesitic glass that 114 dispersed northwards and was recorded as centimetre-thick visible beds in central Kamchatka (Kyle 115 et al., 2011). It has been dated to 6007±38 BP (6950-6740 cal BP) on the basis of five combined ¹⁴C determinations from soils and peat buried by the ash (Braitseva et al., 1997), but new AMS ¹⁴C dates 116 from associated plant macrofossils suggest that this date is too young (F. Pendea, pers. comm.). The 117 118 KS₁ event was the largest Holocene eruption of Ksudach and its tephra extends to northern 119 Kamchatka, rendering it one of the most important isochrons in the region (Braitseva et al., 1997). Fifteen combined ¹⁴C determinations have yielded a weighted mean date of 1806±16 BP (1820-1700 120 121 cal BP) for this event.

122

123 Khangar volcano, in the Sredinny Range, consists of a large crater formed by a sub-caldera eruption 124 in the mid-Holocene. Two closely-spaced events are thought to have occurred at ca. 6900 BP 125 (KHG₆₉₀₀) and ca. 6600 BP (KHG₆₆₀₀), respectively (Bazanova and Pevzner, 2001). The larger of the 126 two events, KHG₆₉₀₀, erupted tephra to the northeast, and visible beds have been identified in 127 northern Kamchatka (e.g. Dirksen et al., 2013). The event has been dated to 6957±30 BP (7920-7690 128 cal BP; Braitseva et al., 1997) or 6872±38 BP (7795-7620 cal BP; Bazanova and Pevzner, 2001) on the 129 basis of combined ¹⁴C dates from associated palaeosols. The distribution of KHG₆₆₀₀ is less well 130 understood. On the basis of distinctive glass geochemistry from five proximal (samples 98106, 98032/2, 98032/4, 98121, 99098/2) and two distal (samples 98052/1, KHG) locations, Kyle et al. 131 132 (2011) reported three distinct populations distinguishable by their K_2O content, that the authors 133 suggested might represent three eruptive events.

Opala is a large stratovolcano in southern Kamchatka. A major explosive eruption in the Late Holocene led to the formation of the Baranii Amphitheater crater at the foot of the volcano and produced the voluminous OP tephra that was dispersed to the northeast (Braitseva et al., 1997; Kyle et al., 2011). This tephra forms a key marker horizon in eastern and central Kamchatka, and it has a very distinctive, glass chemistry characterised by high K₂O and low FeO_{total} and CaO (Kyle et al., 2011). The eruption has been dated to 1478±18 BP (1400-1315 cal BP) using the weighted mean of 11 ¹⁴C determinations on buried soils and charcoal (Braitseva et al., 1995; 1997).

142

143 The highly active Shiveluch composite volcano, northern Kamchatka, has featured at least 42 large 144 eruptions during the Holocene (Ponomareva et al., 2007; in press). Until recently, only a small 145 number of these tephras had been geochemically analysed, eight of which were considered key 146 markers (Ponomareva et al., 2007). Kyle et al. (2011) presented glass geochemistry for 13 Shiveluch 147 eruptions from the mid-Holocene to the last major eruption in 1964 that included data from medial 148 and distal tephrostratigraphies. More recently, Ponomareva et al. (2015) examined over 200 149 proximal sections in the area around Shiveluch, and reported 77 events, of which 42 were classified 150 as major. The authors used Bayesian modelling to refine the ages of the tephras, drawing on 151 radiocarbon dates from organic-rich palaeosols, charcoal and wood associated with the tephras. 152 They provide a comprehensive point dataset of glass geochemistry for 77 Holocene layers, most of 153 which demonstrate a mainly silicic composition. The limited compositional variability between many 154 events presents a challenge to the discrimination of the tephras, however, whereby even small analytical error could potentially lead to miscorrelation of a tephra. Furthermore, it remains to be 155 156 established if proximal geochemical compositions are representative of the full geochemical suite of 157 a given event.

158

159 2.0 Sites and methods

160 Sediment sequences were collected in July and August 2005 from three lakes (Pechora, Lifebuoy and 161 Olive-backed [as attributed during coring expedition]) in northern and central Kamchatka (Fig. 2). 162 Pechora (59°17.613' N, 163°07.766' E, 45 m above sea level [a.s.l.]) and Lifebuoy (59°06.593' N, 163 163°09.141' E, 20 m a.s.l.) Lakes are the most northern sites in Kamchatka from which 164 tephrostratigraphies have been recorded. They are located on the Pacific coast, 300 km north of 165 Shiveluch, and within the trajectory of ash-falls from several large Shiveluch eruptions, as well as 166 those of major eruptions of Ksudach Volcano, 900 km to the south (Braitseva et al., 1997; Kyle et al., 167 2011). Olive-backed Lake (56°12.074' N, 158°51.493' E, 693 m a.s.l.), in central Kamchatka, is 168 situated within the Sredinny mountain range, 160 km southwest of Shiveluch, and within a region 169 that received ash-fall from numerous volcanic systems throughout the Kamchatka Peninsula 170 (Pevzner, 2004, 2011). All three lakes are small in size (<300 m diameter, 3-5 m deep); Olive-backed and Lifebuoy lakes are closed systems without inflowing streams or rivers but Pechora has small inlet 171 172 and outlet streams.

173

Multiple series of cores (each labelled A, B, etc.) were collected from the centres of the lakes using a
5 cm-diameter Livingston corer (Wright, 1967) operated from a rubber boat. Lithostratigraphies
were recorded in the field with respect to depth from surface water level at the coring location.
Sediments were wrapped in plastic film and aluminium foil, secured in plastic drain pipes, and stored
in cold rooms in Stockholm University (Lifebuoy, Olive-backed) or Queen's University Belfast
(Pechora).

180

Samples for AMS ¹⁴C dating were taken from the base of sediment sequences and were measured in the Radiocarbon Dating Laboratory at Lund University. Terrestrial plant macrofossils, where present, were selected but bulk sediment was otherwise sampled. Subsequently, a series of bulk sediment samples was extracted from each of the records for AMS ¹⁴C dating at Queen's University Belfast.

Initial age-modelling, with reference to tephras identified in the respective lakes, suggested no
 appreciable offset in the bulk sediment ages of Pechora and Olive-backed Lakes, but a persistent
 multi-centennial reservoir effect was identified in Lifebuoy Lake (see section 3.2). Additional efforts
 were therefore made to extract terrestrial plant macrofossils from the Lifebuoy Lake sediment
 sequence for AMS ¹⁴C dating.

190

All but two visible tephra layers were subsampled for geochemical analyses from the three lake sites. To corroborate tephrostratigraphical correlations between multiple core sections from individual sites, selected tephras were analysed from multiple cores. Tephra samples were prepared using standard techniques tailored according to the nature of the sediment (preparation methods for each sample are outlined in Supplementary Information). Samples were mounted onto microprobe slides, covered in Buehler EpoxiCure resin. The slides were then ground and polished to expose the surfaces of the tephra shards.

198

199 Major element geochemistry of the tephras was analysed using the electron microprobes at Edinburgh (Cameca SX-100) or Queen's University Belfast (JEOL FEGSEM 6500F) (see Supplementary 200 201 Information for analytical settings). Previous work has shown that these two systems produce 202 comparable data (Coulter et al., 2010). Secondary glass standards Lipari and/or ATho were analysed 203 at each analytical session to ensure that satisfactory operating conditions were achieved (see 204 Supplementary Information for a discussion of instrumental precision). Point analyses with analytical 205 totals <95% were rejected (in accordance with recommendations by Hunt & Hill, 1993), as were any 206 analyses that likely encountered mineral inclusions (indicated by elevated CaO, Al₂O₃, or FeO_{total}-Ti₂O 207 concentrations). Geochemical data were normalised to 100% and were compared between sites, as 208 well as with published glass data from Kamchatkan eruptions (Ponomareva et al., 2007; 2013a; in 209 press; Kyle et al., 2011). Geochemical biplots have been used to examine visually the degree of

compositional similarity between potential correlatives, of which the most discriminatory exampleshave been included in this paper.

212

213 The ¹⁴C and tephra dates were used to produce age-depth models using Clam version 2.2 (Blaauw, 214 2010). Only tephras whose identification was beyond doubt were incorporated into the age-models. 215 Dates for the KS1, OP and KHG₆₉₀₀ tephras are based on published estimates from Braitseva et al. 216 (1997); the KS₂ age was not included as its published age has been called into question (see section 217 1.1). Shiveluch tephras provide direct tie-points between Pechora and Lifebuoy sediment records; 218 their ages have been calculated using the Pechora Lake age-model and they have been incorporated 219 into the Lifebuoy Lake age model. ¹⁴C dates were calibrated using the Northern Hemisphere 220 calibration curve IntCal13 (Reimer et al., 2013). Sediment surfaces were assumed to be of recent age 221 at the time of core collection (AD 2004±5). Smooth splines were chosen as the age-model, applying a 222 smoothing of 0.1 to obtain more flexible models. Tephra layers >1 cm in thickness were excised from 223 the age-depth models as slumps, since they represent abrupt deposition events that interrupted the 224 otherwise smooth sediment accumulation at these sites. All bulk dates from Lifebuoy Lake were 225 rejected due to a persistent offset in age relative to tephra and plant macrofossil-based ¹⁴C determinations. One ¹⁴C date from the base of the Olive-backed Lake record indicated a clear age 226 227 reversal relative to three determinations higher up the profile, and was omitted from the age-model. 228 Rejected dates are shown next to the age models. Modelled age estimates (at 95% level of certainty) 229 for tephras not used in the age model have been rounded outwards to 10 year brackets.

230

231 3.0 Results

¹⁴C determinations are presented in Table 1. Table 2 describes the tephra beds and their

233 correlations. In total, 22 tephra layers (including one mixed layer) were analysed, all of which were

234 characterised by predominantly rhyolitic to dacitic glass. Their compositions lie within the

geochemical fields of Shiveluch, Khangar, Ksudach, and Opala volcanoes (Fig. 3). Complete tephra
geochemical datasets from each of the sites are provided in Supplementary Data, along with
secondary glass standard results. In the following sections, we compare the data to geochemical
data from Ponomareva et al. (in press; Shiveluch tephras denoted by "SH unit") and Kyle et al. (2011;
all other tephras).

240

241 *3.1 Pechora Lake*

242 Seven visible tephra beds were observed in the Pechora Lake sediment sequence, all of which were 243 sampled for geochemical analyses from the PechB core (Fig. 4; Table 2). In the field, a fine, light-244 coloured band recorded as a "possible tephra" was noted in PechC and PechE at depths of 494 cm 245 and 492.5-494.5 cm, respectively, but was not examined further or sampled for analysis. Towards 246 the bottom of the sequence, two thin layers of tephra – Pech 836 and Pech 832 – have chemistries 247 that fall within the Shiveluch compositional field (tephras from which are indicated by the code SH). 248 Only three analyses were obtained from Pech 832, however, and the dataset is too limited to permit 249 any robust comparisons. The Pechora age model suggests that Pech 836 and Pech 832 date to 9310-250 9100 cal BP and 9180-8980 cal BP, respectively, but the tephras do not match any reported 251 Shiveluch beds of this age (Fig. 5a-b). The best geochemical matches are with the closely spaced 252 eruptions SH unit 45 (~8252 cal BP) and SH unit 44 (~8188 cal BP) (Ponomareva et al., in press) but 253 the considerably older age estimates for the Pechora tephras suggest that Pech 836 and Pech 832 254 could be products of other events.

255

Pech 776-778 comprises a rhyolitic to dacitic glass comparable to products from Ksudach. On the
basis of its heterogeneity, Pech 776-778 can be correlated with the KS₂ tephra (Fig. 6a-d). In Pechora
Lake, this tephra has an age-modelled date of 7350-7180 cal BP, suggesting that the KS₂ eruption
occurred several centuries earlier than the currently accepted date (6950-6740 cal BP).

260

261	Pech 768 is an homogenous rhyolitic tephra similar to many products from Shiveluch and has an age
262	modelled date of 7040-6890 cal BP. Two proximal tephra beds – SH unit 40 (~6611 cal BP) and SH
263	unit 39 (~6451 cal BP) – fall close to its timeframe (Ponomareva et al., in press), but SH unit 40 is a
264	trachydacitic glass, and SH unit 39 (previously known as SH_{5600}) appears to be distinguishable on the
265	basis of its AI_2O_3 to FeO_{total} content although the small offset could perhaps be due to analytical error
266	(Fig. 5c-d). Three thicker tephra beds above Pech 768 are similarly attributable to Shiveluch.
267	According to the Pechora age model, Pech 746-749 was erupted in the period c. 6390-6260 cal BP,
268	but it is clearly distinguishable from SH unit 39/SH $_{ m 5600}$ (~6451 cal BP) and SH unit 37 (~5634 cal BP)
269	tephras by its higher SiO ₂ and Al ₂ O ₃ , and lower CaO content (Figs. 5e-f). No glass geochemical data
270	are available for the intervening SH unit 38. Pech 746-749 most closely resembles SH unit 36
271	(previously known as SH $_{ m 4700}$) but unit 36 has a substantially younger age estimate (~5591 cal BP;
272	Ponomareva et al., in press).

273

274 Pech 674-676 has an age-modelled date of 5280-4990 cal BP. Reported Shiveluch tephras of this age 275 include SH unit 35 (~5228 cal BP) and SH unit 34 (SH_{dv}; ~4892 cal BP) (Ponomareva et al., in press). 276 SH unit 35 has a distinctively higher K₂O content and the rhyolitic component of the bimodal SH unit 277 34 has a higher Al₂O₃ content, and both can therefore be dismissed as correlatives (Fig. 7a-b). Over a 278 broader timespan, Pech 674-676 compares most closely with SH unit 36/SH₄₇₀₀ (~5591 cal BP). Pech 279 557-559 is a rhyolitic tephra with a single dacitic shard that lies outside the Shiveluch compositional 280 field. The age model places Pech 557-559 at 3980-3690 cal BP. There are several Shiveluch eruptions 281 around this time, but the best geochemical match is with the silicic component of SH unit 29 (~4010 282 cal BP; Fig. 7c-d). Geochemical data for this unit are based on an ignimbrite deposit, however, and 283 the event has not been associated with wider tephra dispersal. SH unit 32 (~4158 cal BP) and SH unit 284 33 (~4372 cal BP) are also very similar to Pech 557-559 but SH unit 32 seems to be distinguishable on

the basis of its K₂O and CaO content (Fig. 7d). Other Shiveluch tephras around this time can be
differentiated from Pech 557-559 on various oxides.

287

288 Seven ¹⁴C determinations were obtained on bulk sediment. In view of the uncertain relationships 289 between the Shiveluch tephras in Pechora Lake and published datasets, no tephra ages have been 290 used in the age model (Fig. 4). The modelled age for Pech 674-676 is consistent with a ¹⁴C 291 determination from below its counterpart (LB 1061) in Lifebuoy Lake (section 3.2), implying that the 292 Pechora age model is robust at this point. Given the similarities between the Pechora and Lifebuoy 293 Lake tephrostratigraphies, the possible tephra at 494 cm at Pechora Lake may correspond to, and 294 has a modelled age that is consistent with, the KS₁ tephra (section 3.2). The age model indicates 295 moderate (20-38 yr cm⁻¹) sediment accumulation up until c. 5700 cal BP, followed by a period of 296 rapid accumulation (7-20 yr cm⁻¹) until c. 4000 cal BP, and a moderate rate of accumulation (20-35 yr 297 cm⁻¹) thereafter.

298

299 3.2 Lifebuoy Lake

300 Eight visible tephras were recorded in the Lifebuoy Lake sediment sequence (Fig. 8; Table 2). Seven 301 of the tephras have rhyolitic geochemical compositions consistent with Shiveluch. The lowermost 302 tephra, LB 1172-1176, is the thickest of the ash beds at this site, and strongly correlates with Pech 303 746-749 (Fig. 5e-f). LB 1061 similarly compares well with Pech 674-676 (Fig. 7a-b) and LB 906 shows 304 a strong correlation with Pech 557-559 (Fig. 7c-d). The geochemical composition of LB 726 is 305 consistent with that of the KS1 tephra from Ksudach (Fig. 6a-d). Lifebuoy Lake is now the 306 northernmost geochemically-confirmed location of this ash. Two couplets of very thin (3-5 mm) 307 tephras were recorded towards the top of the profile. The chemistries of the three lower tephras 308 most closely resemble several Shiveluch tephras erupted in the last millennium (SH unit 6 to unit 4;

Ponomareva et al., in press), but their major element compositions are not sufficiently distinct to
enable correlations with the recorded events (Fig. 7e-f).

311

312 A bulk sediment sample at the level of the LB 726 tephra yielded a 14 C determination ~ 600 14 C yr 313 older than the reported age of the KS₁ tephra, and called into question the validity of the bulk 314 sediment dates at this site. Two additional dates were then obtained from terrestrial plant 315 macrofossils that confirmed a multi-centennial reservoir effect in the bulk sediments. Consequently, all bulk sediment dates from Lifebuoy Lake were rejected. The ages of the LB 1172-1176, LB 1061 316 317 and LB 906 tephras were established on the basis of the age-modelled dates for their correlatives in Pechora Lake (Pech 746-749, Pech 674-676 and Pech 557-559, respectively). These ages, along with 318 319 the plant macrofossil ¹⁴C dates and the KS₁ tephra layer, were used to construct an age model for 320 Lifebuoy Lake (Fig. 8). The age model suggests rapid sediment accumulation in the lake (6-14 yr cm⁻¹) 321 from 7680-7200 cal yr BP to present. Modelled ages for the four uppermost tephras range from 710-540 cal yr BP for LB 610 to 580-420 cal yr BP for LB 594, and suggest that one of the layers may 322 323 correlate with SH unit 5 dating to ~553 cal BP (Ponomareva et al., in press).

324

325 3.3 Olive-backed Lake

The main core series from Olive-backed Lake, OB Core A (OBA), contained six visible tephras, five of which were confined to the bottom metre of sediment (Fig. 9; Table 2). Parallel cores OB Core B (OBB) and OB Core D (OBD) each contained four tephras, and in OB Core D (OBD), seven tephras were visible including three towards the top of the sequence. Recorded depths for the tephras varied between cores, but spacing between the tephras suggested that cross-correlation between the cores on the basis of tephrostratigraphy was possible. These correlations were confirmed by geochemical analyses of selected tephras from two or more core series. The recorded depths of the

tephras in OBA were taken as primary and were used to designate the tephras, and the relativepositions of the parallel core segments were adjusted accordingly.

335

336 OB 592.5-594 was analysed using a sample from OBD (OBD 599). The geochemistry indicates a 337 heterogeneous rhyolitic population consistent with tephra from Khangar, southern Kamchatka (Kyle 338 et al., 2011; Fig. 10a-d). OB 592.5-594 contains a mixture of the three KHG populations identified by 339 Kyle et al. (2011), but most closely matches samples from the bottom of pumice lapilli beds to the north and north-northeast of Khangar Volcano (samples 98121 and 98032/2; Kyle et al., 2011). We 340 341 therefore propose that OB 592.5-594 correlates with the main KHG₆₉₀₀ event. OB 579 (comprising 342 OBA 579 and OBD 586) shares geochemical similarities with the Khangar tephras but is 343 distinguishable by a higher SiO₂ and K_2O and a lower Al₂O₃ content (Fig. 10a-d). For the time being, 344 this appears to be an unknown event of uncertain provenance, dating to 7400-7270 cal BP. Its high 345 K₂O content may indicate a source in the Sredinny range, such as Ichinsky, less than 100 km to the 346 southwest, which is known to have erupted shortly after the KHG₆₆₀₀ event (Pevzner, 2004; Fig. 1). 347 OB 576 (comprising OBA 575.5 and OBD 583) shows a clear correlation in major element 348 composition with Ksudach tephra KS₂ and Pech 776-778 (Fig. 6). In Olive-backed Lake, its modelled 349 age (7300-7160 cal BP) matches that from Pechora Lake (7350-7180 cal BP).

350

OB 563 is a predominantly rhyolitic tephra with a mixed population distinguishable by SiO₂-Al₂O₃-FeO_{total}-CaO-K₂O values (Figs 3, 10a-d). The high SiO₂ (>76 wt%) population (OB 563a) resembles the KHG tephra, correlating particularly well with Kyle et al.'s (2011) sample 98052/1 (Fig. 10a-d), but it is stratified above the KS₂ tephra, and has a modelled age of 6790-6640 cal BP. The low SiO₂ (<76 wt%) population (OB 563b) lies within the Shiveluch compositional field and compares well with SH unit 37 and SH unit 36/SH₄₇₀₀ (Fig. 5c-d), both of which are, however, younger by approximately a

millennium (Ponomareva et al., in press). It also correlates strongly with Pech 768, although it has a
 marginally higher K₂O content and the modelled ages for the two tephras do not overlap.

359

OB 542 is an homogenous rhyolitic tephra whose geochemistry resembles those of several Shiveluch eruptives (Fig. 5e-f), especially SH unit 36/SH₄₇₀₀, but its modelled age at Olive-backed Lake (5910-5690 cal BP) suggests that OB 542 is approximately two centuries older than unit 36, which was, furthermore, dispersed mainly toward the northeast (Ponomareva et al., 2007; Kyle et al. 2011). The tephra is indistinguishable in major element composition from Pech 746-749 and LB 1172-1176, but its dispersal axis (to the SW of Shiveluch) and its age estimate (younger than Pech 746-749) raise the possibility that this is a previously unreported Shiveluch eruption.

367

368 OB 383-388 (including OBA 383.5-388 and OBD 417-420) correlates strongly with the KS₁ ash (Fig. 369 6a-d). Olive-backed Lake is located close to the 5 cm isopach of this tephra (Kyle et al., 2011). OB 370 383-388 was recorded in the field as a grey tephra and it likely corresponds to the upper layer of 371 pyroclastics deposited at Ksudach during this event (Braitseva et al., 1997). Geochemical analyses 372 indicate that the high-potassium rhyolite OB 369 (comprising OBD 404) correlates with the OP 373 tephra (Fig. 10e-f). OB 369 has a higher SiO₂ content than the OP data published by Kyle et al. (2011) 374 which include geochemistry from proximal, medial and distal deposits. Nevertheless, our data fall 375 within the geochemical range of OP tephra recorded within its more westerly distribution in the 376 Sredinny Range (V. Ponomareva and M. Portnyagin, unpublished data), and it seems likely that our 377 data reflect natural variability within the OP glass. A further tephra was recorded in OBD at a depth 378 equivalent to 364 cm, but was not analysed due to time constraints.

379

The age model for Olive-backed Lake (Fig. 9) includes published ages for the KHG₆₉₀₀, KS₁ and OP
 tephras. In addition, twelve ¹⁴C determinations were obtained, including three from plant

382 macrofossils (LuS-6269, LuS-10895 and LuS-10896). LuS-6269 was treated as an outlier as it was significantly younger than the KHG₆₉₀₀ tephra (OB 592.5-594) and two other ¹⁴C determinations 383 384 above it. 14 C determinations at the level of the KS₁ tephra (OB 383-388) and immediately above the 385 KHG₆₉₀₀ layer (OB 592.5-594) lie within the calibrated age ranges of the tephras. They do, however, 386 appear slightly old relative to the bottom of the slumps associated with these thicker tephras and 387 imply that the tephras may have sunk slightly into the lake sediment. Nevertheless, they indicate 388 that there is no discernible, consistent reservoir affecting the lake sediment at these times. 389 Sediment accumulation rates vary from 48 yr cm⁻¹ towards the base of the core to 19 yr cm⁻¹ 390 towards the top.

391

392 **4.0 Discussion**

393 4.1 Identification of known tephra isochrons

394 Analysis of the distal tephras in this study extends the distribution of two important tephra isochrons 395 to the northern part of Kamchatka. The Ksudach tephras KS₂ and KS₁ can now be confirmed as visible 396 beds across a distance of over 900 km from their source, and provide direct linkage between 397 sedimentary records across the Kamchatka Peninsula. This level of precise correlation greatly 398 facilitates the discernment of synchroneity/asynchroneity in palaeoenvironmental changes on a 399 regional basis, and enables the impact of the eruptions and their ash falls on ecosystems to be 400 assessed (e.g. Andrén et al., submitted; Hammarlund et al., submitted). Both tephras have recently 401 been identified in eastern North America (S. Pyne-O'Donnell, pers. comm.; H. MacKay, pers. comm.), 402 indicating potential to scrutinise past environmental changes on an inter-continental basis.

403

404 Tephra from the Khangar KHG₆₉₀₀ and Opala OP eruptions has been found at Olive-backed Lake,

405 within the area of their previously mapped distributions. The Olive-backed records supplement the

406 available glass geochemical datasets for these events (Kyle et al., 2011). OB 592.5-594 includes all

407 three high and medium K₂O populations identified by Kyle et al. (2011), demonstrating that the
408 three compositions were erupted more or less simultaneously during the larger Khangar eruption.

409

410 4.2 Shiveluch tephra record

411 Numerous Shiveluch tephras are recorded in this study, but no robust correlations with glass data 412 from reported events (Kyle et al., 2011; Ponomareva et al., in press) have been possible. Ostensibly, 413 the distal tephras indicate as many as 11 unrecorded Shiveluch eruptions, mostly dispersed towards 414 the northeast. The similarities in the tephrostratigraphies of the two northern lake sites are reinforced by strong geochemical correlation between paired tephra beds, and clearly document 415 416 three mid-Holocene eruptions during the period in which the two sequences overlap (Fig. 11). Two 417 further events are recorded at Pechora Lake dating to the early Holocene, and four closely spaced Late Holocene events at Lifebuoy Lake are each potential candidates for correlation (geochemically 418 419 and temporally) with one known Shiveluch eruption (SH unit 5). The greater thicknesses of the 420 tephras in the Pechora sediment sequence (an open lake system) compared to those in Lifebuoy (a 421 closed lake system) likely reflect the inwash of ash from the Pechora catchment. Two Shiveluch 422 tephras are also recorded in the Olive-backed Lake sediment sequence that cannot certainly be 423 correlated with published events of a similar age.

424

It is conceivable, however, that the correlation of distal tephra to proximal Shiveluch material has been confounded by one or more factors. Geochemical differentiation during the course of the eruptions may not be fully captured by the proximal deposits against which the tephras from this study have been compared. In this respect, it is notable that strong geochemical similarities have been found between tephras in the neighbouring northern lakes, while the OP geochemistry appears to vary geographically. Differences in instrumental calibration and precision may, on the other hand, have added variance to the proximal and distal datasets, giving the impression of poor correlation.

As secondary glass standards have not been published for the available reference data, we cannot assess the significance of the apparent discrepancies in geochemical composition. Finally, the ages of the published Shiveluch events (Ponomareva et al., in press) have been taken into consideration and in some instances preclude what appear to be suitable geochemical matches (for example, Pech 836 and SH unit 45). Inaccurate age estimates for the proximal or distal tephras (see section 4.3), combined with geochemical subtleties, may therefore mask possible correlations.

438

439 With these caveats in mind, we compare the tephrostratigraphies of Pechora and Lifebuoy Lakes to 440 that of Uka Bog, 150 km to the south (Fig. 11). The Uka sequence closely resembles that of the two 441 northern lakes, insofar as three Shiveluch tephras are recorded between the KS₂ and KS₁ tephras 442 (Dirksen et al., 2013). The tephras are attributed to SH_{5600} (SH unit 39), SH_{4700} (SH unit 36) and SH_{3500} 443 (now known as SH unit 27), respectively; data from the former two were published by Kyle et al. 444 (2011) and are plotted in Figs 5 and 7. On chronological grounds, the oldest of these three events is generally consistent with the age of Pech 746-749 and LB 1172-1176, but our data are clearly 445 differentiated on several oxides (Fig. 5e-f) from proximal (SH unit 39) and distal (SH₅₆₀₀ at Uka Bog) 446 447 tephra from this event (Kyle et al., 2011; Ponomareva et al., in press). The differences cannot easily 448 be explained away as instrumental inaccuracies. Instead, we find a closer correspondence between 449 Pech 768 and SH₅₆₀₀/SH unit 39 which, if true, would imply that either the age of Pech 768 is 450 overestimated, or that the age of SH₅₆₀₀ is underestimated. In contrast, the next two tephra beds 451 (represented in Pechora and Lifebuoy Lakes respectively by Pech 746-749/LB 1172-1176 and Pech 452 674-676/LB 1061) have geochemical signatures that are close to that of SH₄₇₀₀/SH unit 36, but once 453 again, the estimated ages are incompatible. Objectively then, it is not possible to determine with 454 certainty that any of the tephras in the lakes correlates with SH unit 36, as at least two eruptions appear to have produced geochemically indistinguishable glass components as attested by the lake 455 456 sites. The identity of the SH4700 tephra at Uka Bog is similarly called into question. Finally, a tephra at 457 Uka below KS₁ has been correlated on the basis of field observations with SH₃₅₀₀ (SH unit 27) (Dirksen

et al., 2013). Pech 557-559 and LB 906 have an age-modelled date (4020-3720 cal BP) that is close to
the age of SH₃₅₀₀/SH unit 27 (~3750 cal BP), but their geochemistries do not support such a
correlation. Our findings highlight, therefore, several issues relating to the dating and identification
of Shiveluch tephras, and demonstrate some of the difficulties in correlating proximal and distal
tephras.

463

464 4.3 Issues with ¹⁴C dating of Kamchatkan lake sediments

465 It has long been recognised that the dating of bulk lake sediment can be significantly affected by "old 466 carbon" that may be present as dissolved inorganic carbon within freshwater systems, giving rise to 467 a ¹⁴C reservoir effect that results in spuriously old dates (Deevey et al., 1954; Olsson, 1979). 468 Reservoir effects are not restricted to hard water areas, nor are they constant in time, as they can be 469 influenced by a variety of factors including changes in water-atmosphere carbon exchange rates, 470 hydrology or sediment composition (Barnekow et al., 1998; Geyh et al., 1998). Reworked organic 471 material caused by bioturbation or inwash of eroded deposits can also contribute to age reversals in 472 lake sediments (Hammarlund et al., 2003; Blaauw et al., 2011) while downward root penetration, 473 bioturbation or contamination of material in the laboratory, including microbial growth on samples 474 during storage, can lead to younger ages being obtained (Wohlfarth et al., 1998).

475

Varve chronologies and tephra layers have proven useful methods for examining the reliability of
bulk sediment-based ¹⁴C chronologies (e.g. MacDonald et al., 1991; Barnekow et al., 1998). In this
paper, recognised tephra beds – namely, the OP, KS₁ and KHG₆₉₀₀ layers – provide a first order check
on bulk sediment dates. Each of these events has been dated multiple times by different authors
often on bulk terrestrial material immediately below, within or above the individual tephras.
Individual age estimates commonly have large standard deviations (>100 yr), but "best estimates"
have been calculated by combining dates, with the assumption that all age estimates date the same

483 event and that a maximum probability can thus be calculated. The result is usually a ¹⁴C 484 determination with a narrower uncertainty envelope (<50 yr), although it is acknowledged that bulk 485 sediment dates may be contaminated by younger carbon from downward penetrating rootlets 486 (Zaretskaya et al., 2007). Such an effect may explain why the published age for the KS₂ tephra now 487 appears to be too young (see section 1.1). A more sophisticated Bayesian approach has recently 488 been applied for dating Shiveluch tephras, using prior information from multiple, dated 489 tephrostratigraphies to restrain the probable age range of individual beds (Ponomareva et al., in 490 press).

491

492 Of the three lakes examined in this paper, only Lifebuoy Lake reveals a clear reservoir effect in its 493 bulk sediment dates. Lifebuoy Lake is situated in a geological setting similar to Pechora Lake, and the 494 reservoir does not evidently stem from groundwater carbon. At present, we cannot identify the 495 source of the reservoir effect at this lake, although its proximity to the sea (c. 100 m), and a potential 496 input of marine carbon by seabirds, may be a factor. To test this hypothesis, we measured the $\delta^{15}N$ 497 content of a sample of lake sediment from Lifebuoy Lake and compared it to a sample of sediment of 498 approximately the same age from Pechora Lake. The sediment samples were dried, pulverized in a mortar and pestle, weighed into tin capusles analysed at the ¹⁴CHRONO Centre with a Thermo Delta 499 500 V Elemental Analyser – Isotope Ratio Mass Spectrometer (EA-IRMS) for δ^{15} N with an analytical 501 precision of better than 0.15‰. Although both samples showed relatively low δ^{15} N values, the 502 sample from Lifebuoy (2.48‰) being only marginally higher than that from Pechora (1.08‰), this 503 difference may provide some evidence of seabird organic matter input to the sediments of Lifebuoy 504 Lake. Griffiths et al. (2010) demonstrated that heavily seabird-affected ponds in the Arctic can exhibit δ^{15} N values as high as >10‰. The δ^{15} N levels at Lifebuoy appear to be substantially lower 505 506 than this, but the diatom record from Lifebuoy Lake indicates an unusually high nutrient status 507 (Solovieva et al., submitted) that supports the hypothesis of marine bird influence on the lake's ¹⁴C 508 balance.

509 Insofar as can be determined from the lake models of Pechora and Olive-backed Lakes, no reservoir 510 is evident at these sites. At Olive-backed Lake, there is agreement within the 95% probability bracket between the published ages of the KHG₆₉₀₀ and KS₁ tephras and ¹⁴C determinations on bulk sediment 511 associated with their tephras at this site (OB 592.5-594 and OB 383-388, respectively), and the bulk 512 513 sediment dates show no signs of disharmony with the terrestrial plant macrofossil ¹⁴C dates. In the 514 absence of robust geochemical correlations with published Shiveluch eruptions, Pechora Lake lacks a direct means of internally checking for a reservoir effect. The modelled age of Pech 674-676 - a 515 516 correlative of LB 1061 – is consistent, however, with the plant macrofossil-based ¹⁴C determination 517 below LB 1061. The modelled age for the KS₂ tephra at Pechora Lake is also indistinguishable from its 518 modelled age at Olive-backed Lake.

519

520 4.4 Integrity of the Kamchatkan lake tephrostratigraphies

521 On the whole, the tephrostratigraphies of the three lakes examined in this paper compare well with 522 peat and soil sequences in their respective areas: the main tephras that we might expect to see at 523 these locations within the intervals the lake sequences cover are present, and we extend the known 524 distribution of visible KS1 and KS2 tephra beds 150 km northwards. Between parallel cores from each 525 of the lake sites, we observe some minor differences in thicknesses of tephras from core to core, 526 that indicate non-uniform deposition. For the finest, millimetre-thick tephras, this sometimes means 527 that they are absent – or invisible – from some cores (for example, OB 369 – the OP tephra – is not 528 evident in core OBA). Similar "patchiness" of tephras within lake systems has been observed also in 529 cryptotephra studies (Mangerud et al., 1984; Davies et al., 2001). Pyne-O'Donnell (2011) determined 530 that tephra concentrations in lakes were strongly influenced by lake catchment size and the 531 presence of inlet streams, and this has been borne out by the recent study of tephra distributions in lakes following the 2011-2012 eruption of Cordón Caulle, Chile (Bertrand et al., 2014). Inflowing 532 533 streams are therefore likely to explain the greater thicknesses of tephras in Pechora Lake when

compared to Lifebuoy Lake, but it is interesting to note the similarities between the two
tephrostratigraphies that suggests that the lakes captured and recorded the main ashfall events in
this part of northern Kamchatka.

537

538 Notwithstanding concerns about the reliability of bulk sediment-based ¹⁴C dates, we find little 539 evidence to suggest the tephras in this study sank substantially into sediment. Discrepancies in the 540 recorded depths of individual tephras between parallel cores is more plausibly explained by human 541 error during the coring process as the spacing between tephras remains consistent from core to 542 core. Furthermore, dates for the attributed tephras reveal no discrepancies with the lakes' agemodels. Within the age models, however, ¹⁴C determinations relating to the KS₁ and KHG₆₉₀₀ tephras 543 544 in Lifebuoy and Olive-backed Lakes, respectively, fit better with the surface level of these tephras, suggesting potential settling of tephras into "older" surface sediment. 545

546

547 **5.0 Conclusions**

548 We have analysed 22 tephra beds from three lake sediment sequences in northern and central 549 Kamchatka to evaluate the potential of distal tephrochronology in a volcanically active area. All three 550 lakes lie within 300 km of one of Kamchatka's most active volcanoes, Shiveluch, and contain multiple 551 tephras attributable to this volcano. Other tephra beds from more southerly volcanic systems are 552 also recorded, providing robust linkages between the lake sites and other palaeoenvironmental 553 sequences across the Kamchatka Peninsula. Our datasets enhance the characterisation of several 554 key marker beds – the KHG₆₉₀₀, KS₂, KS₁ and OP tephras – and will facilitate the identification of these isochrons in future studies. The Shiveluch tephras underscore the challenges of applying distal 555 tephrochronology in volcanic regions, particularly within the fallout range of a volcanic system as 556 557 highly active and as geochemically homogenous as Shiveluch. Potential hindrances to successful

correlations of distal and proximal tephras include analytical error and dating uncertainty, both of
which may have thwarted the attribution of many of the tephras in this study.

560

561 These issues have clear implications for the ability to relate far-travelled cryptotephras to source, 562 thus to estimate the wider environmental impact of specific eruptions, as well as to utilise the 563 tephras as time-synchronous markers. The study of distal deposits provides a filter through which only the more widely dispersed tephras - those with the best potential for use as extra-regional 564 isochrons - are recorded. Our work highlights the need to verify medial and distal tephra 565 566 attributions though glass geochemical analysis if volcanic events and their impacts are to be reliably reconstructed. Clearly, more research in needed to tie the distal tephras securely to the proximal 567 568 record, be it through an applied dating programme and/or trace and rare element analysis. Further 569 efforts to analyse geochemically distal and proximal reference material within a common analytical 570 session will also be beneficial for establishing robust correlations between tephras.

571

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- 584

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759 Figure captions

760 Fig. 1. Schematic expected tephrostratigraphy for northern (Pechora and Lifebuoy Lakes area) and

- 761 central Kamchatka (Olive-backed Lake area) shown on a ¹⁴C timescale, based on published tephra
- isopachs (Braitseva et al., 1997; Kyle et al., 2011), published sections through Holocene sediments
- 763 (Pevzner, 2010, 2011; Dirksen et al., 2013), and ¹⁴C ages (Braitseva et al., 1997; Bazanova and
- 764 Pevzner, 2001; Pevzner, 2004; 2010, 2011; Ponomareva et al., in press). Only half of the shown
- tephra layers have been geochemically analysed (Kyle et al, 2011); for others their relation to
- proximal tephra beds is not confirmed. Solid lines show major regional tephra layers; dashed lines
- show smaller tephras. Codes for tephra layers: SH general code for all tephra layers from Shiveluch
- volcano; OP Baranii Amphitheater crater (Opala volcano); KS general code for all tephra layers
- 769 from Ksudach calderas; KHG code for tephras from Khangar volcano; SK Svetly Kliuch crater; ICH -
- 770 Ichinsky volcano. Numbers after the tephra codes shown in subscript are approximate ¹⁴C ages.

771

Fig. 2. Location of Pechora, Lifebuoy and Olive-backed lakes in Kamchatka. The locations of the mainvolcanoes discussed in the text and Uka Bog are also indicated.

774

Fig.3. Comparison of tephra glass compositions from a) Pechora Lake, b) Lifebuoy Lake, and c) Olivebacked Lake in relation to some of the main Kamchatkan volcanic systems active in the mid- to Late
Holocene (fields based on geochemical data from Kyle et al., 2011, Ponomareva et al., in press). Field
codes: SH – Shiveluch; OP – Opala; OP_{tr} – Chasha Crater; KS₁, KS₂, KS₃ – Ksudach; KHG – Khangar; KZ –
Kizimen; KO – Kurile Lake Crater; AV –Avachinsky crater.

780

Fig. 4. Schematic tephrostratigraphy and age model for Pechora Lake. The age-model was
constructed using Clam version 2.2 (Blaauw, 2010) and a smooth spline of 0.1. Grey envelopes
indicate the 95% error margin. ¹⁴C determinations (Table 1) contributing to the age model are
labelled to the right of the age-depth curve, and were calibrated using the Northern Hemisphere
calibration curve IntCal13 (Reimer et al., 2013).

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Fig. 5. Selected biplots comparing Shiveluch tephras from Pechora, Lifebuoy and Olive-backed Lakes
with proximal Shiveluch units (Ponomareva et al., in press – tephras designated "SH unit") and

789 medial data from Kyle et al. (2011: SH₅₆₀₀ and SH₄₇₀₀ recorded at Uka Bog, northern Kamchatka).

Fig. 6. Selected biplots comparing Ksudach tephras from Pechora, Lifebuoy and Olive-backed Lakeswith data from Kyle et al. (2011).

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Fig. 7. Selected biplots comparing Shiveluch tephras from Pechora and Lifebuoy Lakes with proximal
Shiveluch units (Ponomareva et al., in press – designated "SH unit") and distal data from Kyle et al.
(2011: SH₄₇₀₀, SH_{dv}, SH₃₅₀₀, SH₂, SH₁).

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Fig. 8. Schematic tephrostratigraphy and age model for Lifebuoy Lake. The age-model was
constructed using Clam version 2.2 (Blaauw, 2010) and a smooth spline of 0.1. Grey envelopes
indicate the 95% error margin. ¹⁴C determinations (Table 1) and tephra attributions (including ages
based on Pechora Lake tephras) contributing to the age model are labelled to the right of the agedepth curve. ¹⁴C dates were calibrated using the Northern Hemisphere calibration curve IntCal13
(Reimer et al., 2013). Dates that were rejected as outliers are shown as open ¹⁴C distributions.

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Fig. 9. Schematic tephrostratigraphy and age model for Olive-backed Lake. The age-model was
constructed using Clam version 2.2 (Blaauw, 2010) and a smooth spline of 0.1. Grey envelopes
indicate the 95% error margin. Radiocarbon determinations (Table 1) and tephra attributions
contributing to the age model are labelled to the right of the age-depth curve. ¹⁴C dates were
calibrated using the Northern Hemisphere calibration curve IntCal13 (Reimer et al., 2013). One date
that was rejected as an outlier is shown as an open ¹⁴C distribution.

810

811 Fig. 10. Selected biplots comparing Khangar and Opala tephras from Olive-backed Lake with data

from Kyle et al. (2011): a-d) OB 592.5-594, OB 579 and OB 563a compared with proximal (98106,

813 98032/2, 98032/4, 98121, 99098/2) and distal (98052/1, KHG) components of the KHG tephra; e-f)

OB 369 compared with proximal, medial and distal data for the OP tephra.

815

Fig. 11. Schematic summary of the tephrostratigraphies from Pechora, Lifebuoy and Olive-backed
Lakes, shown alongside the tephrostratigraphy of Uka Bog, northern Kamchatka (Dirksen et al.,
2011). Tephra designations are indicated to the left of the columns; geochemically-confirmed
attributions are shown to the right (SH indicates Shiveluch origin but event uncertain). Solid lines
indicate robust correlations between the sediment sequences based on geochemical attributes of

- 821 well-characterised tephras. Dashed lines indicate geochemical matches between tephras whose true
- 822 correlations are ambiguous.