1	Using correlated tephras to refine radiocarbon-based age models, Upper and Lower
2	Whitshed Lakes, south-central Alaska
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15 Abstract

Tephra deposits correlated between nearby lakes provide the opportunity to improve age 16 17 estimates of the sediment sequences, even if the ages of the tephras are previously unknown. We 18 explore this potential using cryptotephras and visible tephra deposits in sediment cores from 19 Upper and Lower Whitshed Lakes near Cordova, Alaska. Each tephra was described in terms of 20 visual stratigraphy and shard morphology, and the major-oxide glass geochemistry was analyzed. 21 Independent age models were developed for the cores using radiocarbon ages and profiles of 22 short-lived radioisotopes for the near-surface sediments. Four tephras were correlated between 23 the two lakes based on the magnitude and spacing of magnetic susceptibility peaks and glass 24 major-oxide geochemistry. These correlations confirm agreement of the age models because the 25 independently modeled confidence intervals overlap for each correlated tephra. The stratigraphic 26 correlations were subsequently used to improve the age models by extracting the subset of 27 possible age-model iterations that produce similar ages for each of the four correlated tephras at 28 the two lakes. The iterations that agree within 25 years for each correlated tephra were used to 29 create tephra-matched age models for both lakes, which narrowed the width of the 95% 30 confidence intervals of the age models by 3% overall and reduced the uncertainty in age 31 estimates of the correlated tephras by 34% on average. This synchronization technique may be 32 useful in other studies that have multiple independently dated records with confident 33 stratigraphic correlations. 34

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Keywords: tephrochronology, cryptotephra, age modeling, lake sediments, radiocarbon, Alaska

37 **1. Introduction**

38 Radiocarbon-based age models are the most common method used to date sediment cores 39 that are less than 50,000 years old. The accuracy of these age models depends on the extent to 40 which the constraining ages reliably represent the true timing of sedimentation. The precision of 41 the analyses (the laboratory-reported counting error) accounts for only a small part of the overall 42 uncertainty. More important is the extent to which the material dated actually represents the age 43 of the down core property of interest (Howarth et al., 2013), which is difficult to evaluate 44 without independent evidence. One indicator of the robustness of radiocarbon-based age models 45 is whether the modeled ages of simultaneous events overlap among different cores. Previous 46 studies have used tephra deposits as a test of age-model reliability by correlating tephras in 47 nearby lakes and comparing their modeled ages (e.g., Krawiec et al., 2013). Even if the age of a 48 tephra is unknown, the marker bed still provides a valuable time-line (Lowe, 2011). Dating a 49 tephra deposit in multiple locations also improves the confidence in the age estimate of that 50 deposit, which can then be used as a chronostratigraphic marker in future studies (Lowe, 2011; 51 Kaufman et al., 2012).

52 In studies of multiple sedimentary sequences within a region, it is often desirable to synchronize the records or combine the geochronological information of multiple records. Most 53 54 commonly, this is achieved through 'wiggle-matching', whereby downcore properties are 55 aligned visually (e.g., Hoek and Bohncke, 2001; Burns et al., 2003) or quantitatively (e.g., 56 Marwan et al., 2002; Fohlmeister, 2012). In this study, we present a novel approach that uses 57 tephra deposits correlated between two lakes to not only check the agreement of the age models, 58 but also to further constrain the age-depth relationship. We produced independent age models for 59 the sedimentary sequences of Upper and Lower Whitshed Lakes located near Cordova, Alaska,

60 using radiocarbon and short-lived isotopes. Four tephra deposits were correlated between the two 61 lakes based on their relative stratigraphic position, magnetic susceptibility (MS) profiles, glass 62 geochemistry, and physical characteristics. The correlated tephras were subsequently used to 63 select the age model runs with the closest agreement in predicting the ages of the correlated 64 tephras. This approach allowed for a single best age estimate for each tephra to be calculated 65 using age information from both lakes, and reduced the uncertainty range of the age-model for 66 both sites. In addition to presenting a new approach to age modeling, we report descriptions and 67 geochemical data from 11 tephra samples, thereby contributing to the tephrostratigraphy for the 68 Copper River Delta region.

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70 1.1. Study area

71 Upper Whitshed (60.466° N, 145.918° W) and Lower Whitshed (60.473° N, 145.923° W) Lakes are located in the foothills of the Heney Range about 12 km southwest of Cordova, 72 73 Alaska, at elevations of about 30 and 3 m asl, respectively (Fig. 1). The lakes are both 74 approximately 1 km inland from Prince William Sound on the Gulf of Alaska near Point 75 Whitshed, from which we derive their informal names. Upper Whitshed Lake is slightly larger 76 (1.1 x 0.2 km) than Lower Whitshed Lake (0.7 x 0.3 km). The bathymetry of Upper Whitshed 77 Lake includes several sub-basins divided by ridges, and a maximum depth of about 15 m (Fig. 78 1). No bathymetric data were obtained from Lower Whitshed Lake.



Fig 1. Location maps. (A) Copper River Delta region, showing Whitshed Lakes and other sites
mentioned in text. (B) Alaska state map for reference, WL = Whitshed Lakes. (C) Whitshed
Peninsula showing the two lakes with location of core sites. Topographic base from U.S.
Geological Survey. (D) Bathymetry of Upper Whitshed Lake with core sites shown. Site 2 (S2)

84 is the focus of this study from Upper Whitshed Lake.

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86 The lakes are located near the active Alaska-Aleutian megathrust where changes in land
87 elevation occur on multiple time scales (Garrett et al., 2015), including approximately 1.9 m of

88 uplift in the great Alaska earthquake of 1964 AD (Plafker, 1969). Lower Whitshed Lake received 89 marine sediments during the Little Ice Age, and became isolated as a lacustrine basin during the 90 1964 event (Garrett et al., 2015). The nearest likely source volcanoes for tephras deposited in 91 these lakes are the Aleutian Arc/Alaska Peninsula (AAAP located more than 350 km to the west 92 and southwest) and the Wrangell Volcanic field (located more than 200 km to the northeast). 93 Modern prevailing winds are from the southwest, making deposits from the Wrangell Volcanic 94 field less likely. Glass compositions often distinguish AAAP (Type 1) and Wrangell (Type II) 95 source tephras. Type I sources typically contain more FeO and TiO₂ and less Al₂O₃ and CaO 96 (Preece et al., 1992; Fig. S1). Previous work at Cabin Lake (Zander et al., 2013), 26 km to the 97 northeast, yielded five Holocene tephras mainly from volcanoes along the Cook Inlet of the 98 AAAP, suggesting the same may be true of the Whitshed Lakes tephras.

99

100 **2.** Methods

101 *2.1. Coring*

102 Cores from Lower Whitshed Lake were retrieved in March 2010 from the frozen surface of 103 the lake using a percussion corer and gravity surface corer at a single site (60.472 °N, 145.922 104 °W; Fig. 1). A 262-cm-long percussion core (10-WS-2) and two surface cores were collected 105 (10-WS-1A; 165 cm and 10-WS-1B; 46 cm). Cores were retrieved from Upper Whitshed Lake in 106 June 2011 using a percussion corer and gravity surface corer from a floating platform. To better 107 select coring sites, Upper Whitshed Lake's bathymetry was surveyed prior to coring using a 108 sonar unit with integrated GPS. This study focuses on site 2 (60.466 °N, 145.918 °W, Fig. 1 and 109 2) where the longest sedimentary sequence was recovered, including a percussion core (11-UW-110 2; 427 cm) and a surface core (11-UW-2A; 46 cm).

111 2.2. Geochronology

112 Age models for the sedimentary sequences from both lakes were constructed using the program "Bacon 2.2" (Blaauw and Christen, 2011) based on radiocarbon, lead and artificial 113 radionuclide fallout. Organic matter for ¹⁴C dating was obtained from samples of sediment 0.5-2 114 115 cm thick that were wet-sieved through a 180 µm mesh to find aquatic and terrestrial plant 116 remains including macrofossils of *Picea*, *Tsuga*, bryophytes, and others. The samples were 117 analyzed at the Keck Carbon Cycle AMS Facility at UC Irvine, and dates were calibrated to 118 calendar years prior to 1950 CE (BP hereafter) using IntCal13 (Reimer et al., 2013). 119 Plutonium (Pu) activity profiles were analyzed in surface sediment from both lakes to locate 120 the 1953 onset of nuclear weapons testing, and the 1963 peak fallout (Ketterer et al., 2004). Two 121 profiles of differing resolution were analyzed on the surface cores of both lakes to ensure that the 122 profiles captured the onset of Pu fallout and to precisely locate the depth of peak fallout. Lower 123 Whitshed Lake surface core 10-WS-1A was sampled continuously every 0.2 cm from 0-4 cm 124 depth for one batch. For the second batch, 1-cm-thick samples were taken continuously from 0-125 10 cm, and samples were taken every other cm from 10-30 cm depth. Upper Whitshed Lake surface core 11-UW-2A was sampled every 0.2 from 0-3 cm for the first batch, and every 0.5 cm 126 127 continuously from 1.0-6.5 cm, with increased spacing down to 12.5 cm for the second batch. The 128 samples were analyzed using an inductively coupled plasma mass spectrometer (ICP-MS) at 129 Northern Arizona University. Concentrations of ²¹⁰Pb, ²⁴¹Am and ¹³⁷Cs were measured on Upper Whitshed Lake surface 130 131 core 11-UW-2A. Sampling was done continuously every 0.5 cm from 0-10 cm depth, and the

132 measurements were undertaken by direct gamma assay at the Environmental Radiometric

133 Facility at University College London. Total ²¹⁰Pb was determined via its gamma emissions at

46.5 keV, and ²²⁶Ra by the 295 and 352 keV gamma rays emitted by its daughter isotope ²¹⁴Pb. 134 Unsupported ²¹⁰Pb activities were calculated by subtracting ²²⁶Ra activity (as supported ²¹⁰Pb) 135 from total ²¹⁰Pb activity. Artificially produced radionuclides ¹³⁷Cs and ²⁴¹Am were measured by 136 137 their emissions at 662 and 59.5 keV to determine their down-core profile, which could be 138 ascribed to nuclear weapons testing, as for Pu. A constant-rate-of-supply (CRS) model (Appleby and Oldfield, 1978) was used to produce the ²¹⁰Pb age-depth relation. These analyses were not 139 140 performed on sediments from Lower Whitshed Lake primarily because of expected challenges 141 associated with a major change in the source of sediment that occurred at 1964 (marine to 142 lacustrine transition).

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144 2.3. Age modeling

145 Age models were constructed using the program *Bacon 2.2* (Blaauw and Christen, 2011), 146 which uses a Bayesian statistical approach to construct age-depth relations through the 147 calibrated-age probability distributions of radiocarbon dates, or other age information (i.e., marker horizons with known ages, plutonium peaks, ²¹⁰Pb ages). The sedimentary sequence is 148 149 divided into discrete segments, and millions of Markov Chain Monte Carlo (MCMC) iterations 150 are calculated to estimate the posterior distribution of the age-depth relation given the age control 151 points, their uncertainties, prior estimates of the distribution of sedimentation rates and their 152 autocorrelation, and depths where sedimentation rates are expected to change. The average of the 153 MCMC ensemble, weighted by the log of the objective, is used as the best-fit model. Confidence 154 intervals are calculated as the highest density range of the iterations.

155 The age models for both lakes were further constrained using a novel method to incorporate 156 information provided by the tephra correlations between the two lakes. Code was developed in

157 MATLAB (The MathWorks, Inc.) to identify the iterations from the two independent age models 158 that showed the closest agreement in the ages of the correlated tephras (this code is available in 159 the supplementary material). This was done by calculating the difference between the modeled 160 ages of each correlated tephra for each permutation of the individual models output by Bacon 2.2 161 for each lake. The permutations in which the modeled age for each tephra differed by less than 162 25 years were selected for use in the 'tephra-matched' age models. Thus, to be included in the 163 'tephra-matched' age model of one lake, the ages of the four correlated tephras in the model 164 iteration must be within 25 years of all four tephra age estimates of at least one model iteration 165 from the other lake. The 25-year threshold was chosen to maximize the synchronization of the 166 two age models while maintaining enough of the model iterations to calculate robust 95% 167 confidence intervals. The choice of matching threshold has little influence on the overall 168 outcome (see section 3.5 and Table 4).

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170 *2.3. Tephras*

171 Tephras were located based on visual inspection of the sediment cores, and by spikes in 172 magnetic susceptibility (MS). The tephra beds are generally lighter in color, and have higher MS 173 than the organic-rich background lacustrine sediments. Four tephras comprise visually distinct 174 beds that were sampled from the cores. In addition, seven zones containing cryptotephra 175 (disseminated tephra grains that do not form visible bed) were sampled. Five of these 176 cryptotephra samples were chosen based on notable spikes in MS, and 1-cm-thick samples were 177 taken at the location of highest MS spikes. For two samples, age information was used as a guide 178 to prospect for the Katmai-Novarupta ash (1912 CE), as there is evidence that fallout from the 179 eruption reached the Cordova area (Payne and Symeonakis, 2012). Again, 1-cm-thick samples

180 were taken. If the tephra bed was visible on the core face, samples ranging from 0.2 to 1 cm thick 181 were taken while avoiding adjacent lacustrine sediments. The tephra samples were named 182 according to their depth within the individual core, which is registered to the top of the core tube 183 rather than the composite depth below lake floor (BLF). Sediment was viewed under a 184 petrographic microscope to confirm the presence of volcanic ash; grain size and shard 185 morphologies were described for all tephras.

186 Major- and minor-element glass geochemistry for each tephra was analyzed at Concord University. For the visible tephra layers, small samples were taken (<1 cm³) across the thickness 187 of the visible layer. For the non-visible beds, 1-3 cm³ of material was sampled across a 1-cm-188 189 thick interval associated with an MS peak. The cryptotephra samples were soaked in $\sim 10\%$ 190 hydrogen peroxide to remove organic material, then separated by density in a lithium 191 heteropolytungstate solution with a density of 2.5 g/cm³. The resulting concentrates were rinsed 192 and a portion of each was mounted following a variation of the technique described by Kuehn 193 and Froese (2010). Samples were pipetted into holes drilled in acrylic discs, dried, embedded in 194 epoxy, polished, and carbon coated. The samples were analyzed on an ARL SEMQ electron 195 microprobe using the instrumentation, analytical conditions, primary and secondary standards, 196 and normalization procedures of Zander et al. (2013) with only a change in spectrometer type for 197 Si and Al (from wavelength-dispersive to energy-dispersive to achieve higher count rates and 198 improved precision). Because the samples typically contained only a small number of tephra 199 grains, two or three analyses were collected from most grains. Geochemical similarity of 200 stratigraphically correlated tephra was determined by comparing plots of data and by using the 201 similarity coefficient (SC) of Borchardt et al. (1972). We weight sodium oxide at 50% in the SC 202 calculation due to larger errors associated with the measurement of this element.

203 **3. Results**

204 *3.1. Overview of stratigraphy*

205 Upper Whitshed Lake surface core 11-UW-2A was correlated with the percussion core 11-206 UW-2 based on a tephra located at 36.5 cm tube depth in the surface core and at 21.5 cm tube 207 depth in the percussion core, indicating that the percussion core is missing the uppermost 15 cm 208 of sediment (Fig. 2). The missing sediments are expected when using the percussion corer and 209 necessitate the use of a composite depth scale. All depths reported hereafter are distance below 210 the lake floor (BLF), unless otherwise stated. The 442-cm-long composite sedimentary sequence 211 recovered from site 2 can be broken into two major units (Fig. 2). The oldest sediments below 212 372 cm (Unit 1) are generally massive light grayish brown (2.5Y 4/2), inorganic silty clay. 213 Above 372 cm (Unit 2), the sediments are massive dark brown (10YR 2/2) sapropelic 214 diatomaceous clayey silt. In addition, three tephras are visible along the core face, none thicker 215 than 1 cm.



Fig. 2. Lithostratigraphy of (A) Upper Whitshed Lake cores 11-UW-2/2A, and (B) Lower 217 218 Whitshed Lake cores 10-WS-2 and -1A. The linescan image of the surface core (10-WS-1A) has 219 been stretched to approximate the depth of percussion core 10-WS-2. Horizontal bands show the 220 location of tephra samples taken from visible beds (green) and cryptotephra (red). Tephra 221 correlations are indicated by roman numerals (I, II, III, IV) to right of the horizontal bands. The 222 uppermost two tephra samples from Upper Whitshed Lake (taken from 2.5 and 5 cm) are not 223 distinguishable at this depth scale and thus are represented by a single red bar. Magnetic 224 susceptibility is plotted on two scales to highlight smaller peaks (gray corresponds to the bottom 225 scale). Depths are relative to the lake floor (BLF). The calibrated ages of radiocarbon samples 226 are noted on the left of the linescan images.

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228 The Lower Whitshed Lake sedimentary sequences (surface core 10-WS-1A and percussion 229 core 10-WS-2) were correlated using distinctive color changes and peaks in MS, which suggest 230 that percussion core 10-WS-2 is missing the uppermost 3.5 cm of sediment. The total recovered 231 composite sequence is 266 cm long. All depths reported hereafter are distance below the lake 232 floor, unless otherwise stated. The Lower Whitshed Lake composite sedimentary sequence can 233 be divided into three major units (Fig. 2). The oldest unit (Unit 1), below 103.5 cm, is massive 234 dark brown (10YR 2/2) sapropelic diatomaceous clayey silt. From 103.5 to 4 cm (Unit 2), the 235 sediments are gray (5Y 4/2) inorganic clayey silt with 1- to 3-mm-thick laminations. The 236 uppermost 4 cm (Unit 3) of sediment is brown (10YR 2/2) sapropelic diatomaceous clayey silt.

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238 3.2. Upper Whitshed Lake age model

The concentration of ²¹⁰Pb from surface core 11-UW-2A increases roughly exponentially 239 240 upward in the sedimentary sequence (Fig. 3; Table S1). The constant-rate-of-supply (CRS) 241 model suggests that sedimentation rates increase from 0.3 mm/year at 8 cm up to 0.8 mm/year in 242 the upper 2 cm of the core. Three different radionuclides produced from nuclear weapons testing were measured on surface core 11-UW-2A: ²³⁹⁺²⁴⁰Pu (Table S2), ¹³⁷Cs, and ²⁴¹Am (Table S1; 243 Fig. 3). The onset of ²⁴¹Am fallout is clearly observed between 4.25 and 3.75 cm, suggesting that 244 sediment deposited in 1953 is near 4 cm in this core. This is in agreement with the ²¹⁰Pb CRS 245 246 model, which also suggests that 1953 is represented between 4.25 and 3.75 cm. The 1963 peak in 247 fallout is not well defined by the radionuclide profiles, most likely a result of sediment mixing. 248



Fig. 3. Profiles of ²¹⁰Pb and radionuclides produced by nuclear weapons testing, Upper Whitshed Lake surface core 11-UW-2A. (A) Estimated ages from a constant-rate-of-supply model based on (B) the unsupported ²¹⁰Pb activity. Activities of artificial nuclides include: (C) ²⁴¹Am, (D) ¹³⁷Cs, and (E) ²³⁹⁺²⁴⁰Pu (two analytical batches shown). Bars are ± 1 SD analytical errors. Data are listed in Table S1 and S2.

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256 The *Bacon* age model for the Upper Whitshed Lake sedimentary sequence (Table S3) was 257 constrained by the age of the sediment surface (2011), the 1953 onset of nuclear weapons testing 258 at 4 cm, the middle and lowest ages defined by the ²¹⁰Pb CRS model (1947 at 4.25 cm, and 1827 259 at 8.25 cm), and 13 of the 15 radiocarbon dates from the two cores at site 2 (Table 1). Two 260 radiocarbon ages were rejected because they were not stratigraphically aligned in the sediment 261 sequence as defined by other age information (Fig. 4). An additional radiocarbon sample from 262 Upper Whitshed Lake has a calibrated age range that does not overlap with the 95% confidence 263 interval of the age model. This sample has an analytical uncertainty of ± 400 years, but there was 264 not enough evidence to reject the age, it is therefore used in the Bacon age model. Because there 265 are no major changes in lithology to suggest a change in sedimentation rate in the Upper 266 Whitshed Lake sequence, we used the slope of a best-fit line through the non-rejected

radiocarbon dates as the expected accumulation rate (34 years/cm) in the *Bacon* model. The
default accumulation rate shape parameter (1.5) was used. The model was run with segment
widths of 4 cm, a value chosen to maximize the model's resolution and smoothness without
excessively long computational run times. Larger segment widths can result in an unrealistic
jagged pattern of sedimentation rate changes. The output of the original, independent Upper
Whitshed Lake age model can be viewed in Fig. S3.

- 273
- 274 *3.3. Lower Whitshed Lake age model*

275 Plutonium is first detected in surface core 10-WS-1A at 9.5 cm, which is interpreted as the 276 onset of nuclear weapons testing in 1953 (Ketterer et al., 2004). Plutonium activity increases 277 upward and peaks at 1.7 cm (Fig. 4). However, a major lithological change at 4 cm is associated 278 with a marked change in sedimentation rate due to the isolation of the lake basin from the Gulf of 279 Alaska (Garret et al., 2015). This change in sedimentation rate strongly influences the 280 concentration of plutonium in the sediment, unrelated to the rate of fallout. To account for this, 281 and to more accurately locate the peak fallout in the core, plutonium activity per unit mass (Bq kg^{-1}) was converted to a flux (i.e. activity per unit mass per year; Bq cm kg^{-1} year⁻¹) by 282 283 multiplying by simple estimates of sedimentation rates above and below the lithological change 284 at 4 cm. These sedimentation rates were calculated based on the onset of plutonium activity, and 285 two radiocarbon ages obtained from within Unit 2. The peak of plutonium flux occurs at 4.5 cm, 286 suggesting this is the approximate depth of sediment deposited in 1963 (Fig. 4). Because this 287 peak is essentially defined by the sharp change in sedimentation rate superposed on an upward-288 increasing trend, there is some uncertainty about the placement of the peak in fallout. However, 289 the sedimentation rate change associated with a marine-to-lacustrine transition was most likely

caused by uplift during the 1964 Great Alaska Earthquake (Garrett et al., 2015), suggesting that
1964 is represented near 4 cm depth.

292 The age model for the sedimentary sequence recovered from Lower Whitshed Lake (Table 293 S4) was based on the age of surface core, the onset and peak of nuclear weapons testing as 294 recorded in the plutonium profile, and 11 radiocarbon dates. The two basal ages from Lower 295 Whitshed Lake are out of stratigraphic order, but it is difficult to assess which is more accurate, 296 so both are included. Three different prior estimates of sedimentation rates were input into the 297 *Bacon* program based on changes in stratigraphy: (1) from the base of the sequence (265.5 cm) 298 to 103.5 cm, an expected sedimentation rate of 65 years/cm was used, based upon radiocarbon 299 ages in this segment; (2) between 103.5 and 4 cm, a sedimentation rate of 3 years/cm was used, 300 based upon two radiocarbon dates and the 1953 onset of nuclear weapons testing at 9.5 cm; and 301 (3) from 4 to 0 cm, a rate of 11 years/cm was based on an extrapolation that assumed the 302 sedimentation rate from 9.5 to 4 cm was consistent with the rest of Unit 2, and that the 303 sedimentation rate shifted from 4 cm to the core top. The default accumulation shape parameter 304 (1.5) was used for each of these segments. A segment width of 2 cm was selected to maximize 305 the resolution and smoothness of the model output without excessively long run times. The 306 output of the original, independent Lower Whitshed Lake age model can be viewed in Fig. S4. 307

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Table 1

Lab ID (UCIAMS)	Top tube depth (cm)	Bottom tube depth (cm)	Top depth BLF (cm)	Bottom depth BLF (cm)	¹⁴ C age (yr BP)	Calibrated age (BP) ^b	Material
Upper Wh	itshed La	ake (surfac	re core 1	1-1/W-2A a	nd percuss	ion core 11-1	1/W-2)
107549 ^a	19.5	21.5	19.5	21.5	1140 ±	1055 ±	Non-specific plant remains, <i>Daphni</i>
98669	23.0	24.0	38.0	39.0	1815 ± 50	100 ± 91	Two <i>Tsuga</i> needles, one <i>Picea</i>
104760	81.0	82.0	96.0	97.0	3625 ± 35	3937 ± 45	Terrestrial leaf fragments, small wood fragments
107547	111.0	112.0	126.0	127.0	4135 ± 20	4679 ± 112	Pressed non-specific organics, bryophyte twig, leafy material
104761°	130.0	131.0	145.0	146.0	2460 ± 20	2593 ± 118	<i>Picea</i> needles, bryophyte twig, <i>Tsug</i> needle, bryozoan statocyst, non- specific organics
107548	151.5	152.5	166.5	167.5	4765 ± 20	5523 ± 54	Bryophytes, terrestrial leaves, sedge (Cyperaceae) achene
100080	180.5	181.5	195.5	196.5	5640 ± 30	6423 ± 34	Leaf fragment, stem fragments - terrestrial
104762	224.0	225.0	239.0	240.0	5960 ± 30	$6787\ \pm\ 51$	Small terrestrial leaf fragments
121202	263.5	264.5	278.5	279.5	7450 ± 20	$8263\ \pm\ 59$	Large plant spike
104763	276.0	278.0	292.0	293.0	$ \frac{20}{8840} \pm 400 $	9943 ± 509	Terrestrial leaf fragments
128102 ^c	279.5	280.5	294.5	295.5	8030 ± 30	8907 ± 109	Leaf fragment
121203	302.5	304.5	317.5	319.5	6830 ± 30	7660 ± 30	Chitin, leaves, twigs, stems, seed capsules
100081	347.0	348.0	362.0	363.0	9530 ±	$\begin{array}{r} 10870 \hspace{0.1 cm} \pm \\ 179 \end{array}$	Leaf fragments and bryophyte twigs
104764	380.5	381.5	395.5	396.5	11070 ± 40	12940 ± 74	Terrestrial leaf fragments (from sm shrub), lots of bryophyte twigs
100082	418.0	420.0	433.0	435.0	12430 ± 100	14560 ± 262	Bryophyte, unidentifiable fragments Ericaceae seed, leaf fragments
<u>Lower Wh</u>	itshed La	ake (percu	ssion cor	e 10-WS-2)	<u>)</u>		ý Đ
76307	44.5	45.5	48.0	49.0	135 ± 20	134 ± 127	Hemlock (<i>Tsuga</i>) needle fragments, bryophyte capsules
82286	94.0	95.0	97.5	98.5	175 ± 20	184 ± 130	<i>Tsuga</i> needles, alder (<i>Alnus</i>) leaf fragments, conifer seed, wood fragments
76308	105.5	106.5	109.0	110.0	455 ± 15	511 ± 6	<i>Picea</i> needles and twigs, <i>Tsuga</i> needle
82287	129.0	130.0	132.5	133.5	1970 ± 15	1915 ± 20	Two <i>Picea</i> and one <i>Tsuga</i> needles, conifer seed wing, conifer seed fragment
82288	146.0	147.0	149.5	150.5	2875 ± 20	2996 ± 49	Conifer wing fragment, <i>Picea</i> seed and needles, chitin from aquatic insects

310	Radiocarbon	ages from	Upper and Lower	Whitshed 1	I ake sediment cores	2
510	Kaulocalooli	ages nom	Upper and Lower	wintsheu i	Lake seument cores	.,

82289	166.0	167.0	169.5	170.5	3960 ± 30	4431 ± 54	All aquatic material, caddisfly case
82290	190.0	192.0	193.5	195.5	$\begin{array}{c} 5130 \ \pm \\ 20 \end{array}$	$5906~\pm~14$	All aquatic chitin
82291	200.0	201.0	203.5	204.5	5635 ± 20	6420 ± 21	<i>Cladocera</i> chitin, terrestrial leaf vein, alder leaf, moss fragments
82292	221.0	221.0	224.5	224.5	7525 ± 20	8363 ± 14	All aquatic; chitin, chironomid head fragments, non-specific plants (moss branches?)
76309	250.0	251.0	253.5	254.5	9355 ± 25	$\begin{array}{r} 10570 \ \pm \\ 63 \end{array}$	Unspecified leaf fragments
82293	261.0	263.0	263.5	266.5	8875 ± 30	$\begin{array}{l} 10030 \hspace{0.1 cm} \pm \\ 116 \end{array}$	Terrestrial leaf fragments, aquatic chitin, <i>Najas</i> (floating leaf aquatic plant)

311 ^a Age from surface core 11-UW-2A, all others are from percussion cores

^bMedian probability age from Calib 7.0 (Reimer et al., 2013); $\pm =$ one-half of 1 σ range

- 313 ^cRejected age
- 314



Fig. 4. Age models for sediment cores from (A) Upper and (B) Lower Whiteshed Lakes. Insets show uppermost portions of age models in detail and radionuclide profiles used to constrain ages near the surface. Tick marks along the depth scale show the locations of tephra samples, green indicates samples taken from visible beds, and red indicates samples of cryptotephra. Numerals (I, II, III, IV) adjacent to these tick marks indicate the correlations between the lakes. The uppermost two tephra samples from Upper Whitshed Lake (taken from 2.5 and 5 cm) are not distinguishable at this depth scale and thus are represented by a single red bar. Error bars for ¹⁴C

ages are 1σ calibrated age ranges (data listed in Table 1). Complete input and outputs for these age models are in Tables S3, S4, S6, and S7.

325

326 *3.4. Tephrostratigraphy*

327 A total of 11 tephra samples were collected from the two lakes, seven from Upper Whitshed 328 Lake and four from Lower Whitshed Lake (Table 2 summarizes the tephrostratigraphy of the two 329 lakes). Three of the Upper Whitshed Lake samples were collected from visible beds and the 330 other four samples were collected from zones of disseminated cryptotephra with high MS values 331 (Table 3; Fig. 3). Only one tephra was visible in the core from Lower Whitshed Lake, while the 332 other three samples were taken from zones of disseminated tephra indicated by MS peaks. All of 333 the samples from visible beds and all but two of cryptotephra samples yielded distinct 334 geochemical populations (Fig. 5 and 6). Overall, the glass chemistries are indicative of primarily 335 AAAP (Type I) sources, although some of the data overlap the boundary between Type I and 336 Type II compositional fields (Fig. S2). 337 The glass geochemistry supports stratigraphic correlations of four tephra beds between the 338 two lakes: 10-WS-2-1-104.5 with 11-UW-2A-13, 10-WS-2-127.5 with 11-UW-2A-36.5, 10-WS-339 2-189 with 11-UW-2-163.5, and 10-WS-2-198.5 with 11-UW-2-2-185 (note that tephra sample

340 IDs use tube segment numbers and depths, and not composite depth BLF). Table S5 includes the

341 complete geochemical results for Whitshed Lakes tephras. Ages reported in this section (3.4) are

based on the independently produced age models without the tephra-matching routine to refine

343 the models; this is done in order to present the original chronological uncertainty associated with

344 these deposits prior to correlation.

345	Two samples were analyzed in an attempt to identify glass shards from the 1912 eruption of
346	Novarupta, which is interpreted to have likely deposited tephra near Cordova by Payne and
347	Symeonakis (2012). The eruptive material of Novarupta was derived from a zoned magma
348	chamber, and has a wide variety of compositions, ranging from $58.5-78.0\%$ SiO ₂ (Hildreth,
349	1987). Sample 11-UW-2A-2.5 (Concord University ID: CU1286, 1975 \pm 7 CE) is not associated
350	with an MS peak and is too young to contain a primary deposit from Novarupta. 11-UW-2A-5
351	(CU1160, 1926 \pm 22 CE) is associated with a minor MS peak (3.3 SI units) and has a modeled
352	age that overlaps 1912 CE. Sample 11-UW-2A-2.5 contains two well-defined major populations
353	(Fig. 6): (1) a heterogeneous population with a SiO ₂ range of 58–75 wt%, and (2) a
354	homogeneous high silica population with SiO ₂ \sim 78 wt%. The latter is an excellent match (SC
355	0.97) for the high silica end-member composition of Novarupta 1912 and likely represents
356	reworked material from the Novarupta eruption. The heterogeneous population, however, plots
357	away from the lower silica components of the 1912 eruption (Table S5) and likely represents a
358	different event. Sample 11-UW-2A-5 (CU1160) contains the same two populations, although the
359	~78 wt% SiO ₂ population is represented only by a single analysis (fewer shards were analyzed in
360	this sample, so this may be due to sampling bias).
361	11-UW-2A-13 (CU1161, 464 \pm 325 BP) and 10-WS-2-104.5 (CU1278, 382 \pm 107 BP) are
362	correlated based on their independently modeled ages, similar-magnitude MS peaks, and glass
363	geochemistry (SC = 0.97). Both samples contain mainly and esitic glass (Fig. 5), with a
364	secondary population of more silicic glass (33% of grains in 11-UW-2A-13; 19% in 10-WS-2-
365	104.5). The geochemical composition of most of these shards overlap with the distribution

defined by population 1 in 11-UW-2A-2.5 (CU1286) described above.

367	11-UW-2A-36.5 (CU1162, 1654 ± 196 BP) and 10-WS-2-127.5 (CU1149, 1748 ± 189 BP)
368	are correlated based on their independently modeled ages, similar physical characteristics, high
369	MS values, and glass geochemistry (SC = 0.94). Both samples contain rhyolitic glass with little
370	compositional variability. The geochemistry of this sample is indistinguishable (SC 0.97; Table
371	S5) from sample 10-CB-1-C-102 (CU1148, 1303 ± 55 BP) at Cabin Lake (Zander et al., 2013),
372	but the ages differ, suggesting either that the two lakes contain tephras of different eruptions
373	from the same source, or that the Cabin Lake age may be somewhat inaccurate.
374	The stratigraphic levels represented by samples 11-UW-2-163.5 (CU1157, 5863 \pm 229 BP)
375	and 10-WS-2-189 (CU1150, 5498 ± 291 BP) are correlated based on their independently
376	modeled ages and distinctive MS stratigraphy in this part of the core. The glass geochemistry of
377	these samples is relatively scattered ranging from 59-80% silica. Overall the geochemical data of
378	the samples overlap, but there are significant differences. Sample 11-UW-2-163.5 contains a
379	mixture of andesitic/dacitic glass shards and fewer rhyolitic shards. Sample 10-WS-2-189
380	contains a mixture of mainly rhyolitic glass shards with few andesitic/dacitic shards. The high
381	silica modes yield an SC value of 0.83, but this is based on only six data points from 11-UW-2-
382	163.5. These samples may include reworked material from multiple eruptions, and this
383	interpretation is supported by evidence of subtle rounding of glass shards in 11-UW-2-163.5.
384	11-UW-2-185 (CU1158, 6442 \pm 140 BP) and 10-WS-2-198.5 (CU1151, 6246 \pm 199 BP) are
385	correlated based on independently modeled ages, similar magnitude MS peaks, and glass
386	geochemistry (SC = 0.93). Both samples contain homogeneous rhyolitic glass.
387	11-UW-2-355 (CU1159, 11370 \pm 410 BP) contains a bimodal population of dacitic/rhyolitic
388	glass. No equivalent is found in the Lower Whitshed Lake cores because it is older than the
389	oldest recovered sediments from the lower lake. This bed may correlate with sample 11-CB-4-4-

390 269 (CU1154, 10,636 \pm 195 BP) at Cabin Lake (Zander et al., 2013); both samples contain the

391 same bimodal compositional distribution (Table S5). The age estimates differ slightly, but the

392 age control for the Cabin Lake sample is poor, allowing for the possibility of a correlation.

393

Table 2

395 Tephras in sediment of Upper and Lower Whitshed Lakes, with age estimates based on

independent and tephra-matched age models and descriptions of tephra beds (if visible) and

397 shard morphology.

	Concord	Depth	Thielmoor	Indonandanthy	Tephra-		
Sample ID	ID	(cm)	(cm) ^a	modeled age ^b	age ^b	SC ^c	Description
.							•
<u>Upper Whits</u>	shed Lake						
11-UW-	CU1286	2.5	-	1975 ± 7 CE	$1975 \pm$	-	Rare frothy pumice and angular blocky
2A-2.5					6 CE		shards smaller than 50 µm.
11-UW-	CU1160	5	-	$1926 \pm 20 \text{ CE}$	1926 ±	-	Rare frothy pumice and angular blocky
2A-5	011171	12	0.2	464 . 225 DDd	20 CE	0.07	shards smaller than 60 μ m.
11-UW-	CUII6I	13	0.2	$464 \pm 325 \text{ BP}^{d}$	393 ±	0.97 (T)	Correlated with 10-W S-
2A-13					103 BP	(1)	2-104. Light tan bed with sharp contacts. Bubble walled shards up to 130 um are
							dominant with frothy pumice and blocky
							shards also present.
11-UW-	CU1162	36.5	0.5	$1654~\pm~196~BP$	$1719 \pm$	0.94	Correlated with 10-WS-
2A-36.5					160 BP	(II)	2-127.5. Light tan bed with sharp
							contacts. Bubble-walled shards up to 200
							µm are most common. Also present are
							equant blocky shards, from y pumice with
							shards
11-UW-	CU1157	178.5	-	5863 ± 229 BP	5791 ±	0.83 ^e	Correlated with 10-WS-
2-163.5					135 BP	(III)	2-189. Dominantly equant blocky shards
							up to 120 µm, with some frothy pumice,
							and occasional bubble-walled shards.
11-UW-	CU1158	200	1.0	$6442 \pm 140 \text{ BP}$	6397 ±	0.93	Correlated with 10-WS-
2-185					171 BP	(IV)	2-198.5. Medium brown bed with diffuse
							to 120 ym. Bybble welled sherds and
							for the numice are also present
11-UW-	CU1159	370	_	11370 ± 410	11310 ±	_	Dominantly equant blocky shards, and
2-355				BP	456 BP		some elongate shards, which may be
							bubble-walled shards. The largest shards
							are 180 µm.
<u>Lower Whits</u>	<u>shed Lake</u>						
10-WS-	CU1278	108	-	$382\pm107\;BP$	$393~\pm$	0.97	Correlated with 11-UW-2A-13. Mainly
2-104.5					103 BP	(I)	bubble-walled shards and tricuspate
							forms. Frothy pumice with elongate
							vesicles and blocky shards are also
							present. The largest shards are 120 µm

10-WS- 2-127.5	CU1149	131	0.5	1748 ± 189 BP	1719 ± 160 BP	0.94 (II)	Correlated with 11-UW-2A-36.5. Light tan bed with sharp contacts. Bubble- walled shards are most common. Equant and tabular blocky shards, elongate needle shaped shards, and frothy pumice with elongate vesicles are also present. The largest shards are 180 µm.
10-WS-	CU1150	192.5	-	$5703~\pm 233~\mathrm{BP}$	$5791 \pm$	0.83 ^e	Correlated with 11-UW-
2-189					135 BP	(III)	2-163.5. Mainly blocky equant shards, with tabular blocky shards and bubble-walled shards also common. Frothy pumice is rare. The largest grains are 140 μ m.
10-WS-	CU1151	202	-	$6246~\pm~199~\mathrm{BP}$	$6397 \pm$	0.93	Correlated with 11-UW-
2-198.5					171 BP	(IV)	2-185. Blocky shards are the most common, with both equant and tabular forms. Bubble walled shards are also common. Elongate shards and frothy pumice are rare. The largest grains are 110 μm.

^a "—" = tephra not visible on the core face; sample thickness was 1 cm for these cryptotephra samples ^b error range is equal to half the width of the 95% confidence interval 398

399 400 ^c SC = Similarity Coefficient (Borchardt et al., 1972); correlated samples are noted by numerals in parenthesis

401 ^d BP = cal yr before 1950 CE

402 ^e SC value from high-silica modes of 10-WS-2-189 (major population) and 11-UW-2-163.5 (secondary population)

403 **Table 3**

404 Summary of normalized major-element compositions of tephra glass from Upper and Lower Whitshed Lakes. Complete data in Table 405 S5. Outlying data points are generally excluded here.

Sample ^a		SiO ₂	TiO ₂	Al_2O_3	FeO _t ^b	MnO	MgO	CaO	Na ₂ O	K_2O	P_2O_5	Cl	Total	n ^c
Inn on Whitehod I also														
<u>Upper Whitshea Lake</u>														
Lower silies and	Moon	50.70	1.20	16.01	7.01	0.10	2 75	613	2.91	1.80	0.20	0.12	100	20
member of mixing trend	StDov	1.05	0.07	0.22	0.64	0.19	2.75	0.15	0.40	0.17	0.29	0.12	100	20
Higher silica and	Mean	74 57	0.07	13.02	1.56	0.03	0.23	1.82	4 15	3.02	0.03	0.02	100	8
member of mixing trend	StDev	0.41	0.02	0.31	0.10	0.07	0.02	0.23	4.15 0.27	0.19	0.04	0.17	100	0
Highest silica population	Mean	78.06	0.02	12 32	1.20	0.02	0.02	0.23	4.03	3 10	0.03	0.02	100	14
Tingitest since population	StDev	0.45	0.15	0.18	0.12	0.04	0.10	0.75	4.05	0.09	0.02	0.21	100	14
11-UW-2A-5 (CU1160)	SiDev	0.45	0.02	0.10	0.12	0.05	0.01	0.05	0.50	0.07	0.05	0.02		
Higher silica end member	Mean	74.52	0.31	14.15	1.54	0.08	0.37	1.78	4.21	2.86	0.07	0.15	100	6
	StDev	0.30	0.03	0.24	0.09	0.03	0.03	0.11	0.21	0.24	0.04	0.03		
Highest silica (similar to Novarupta/CU1286)		77.81	0.15	12.28	1.06	0.09	0.09	0.81	4.39	3.13	0.01	0.22	100	1
Overall Average	Mean	70.98	0.51	14.62	2.94	0.11	0.82	2.69	4.45	2.62	0.12	0.17	100	11
	StDev	5.34	0.31	1.09	2.04	0.05	0.72	1.44	0.41	0.41	0.08	0.06		
11-UW-2A-13 (CU1161)														
Low-silica mode	Mean	60.34	1.16	16.15	7.63	0.23	2.66	5.56	4.02	1.85	0.30	0.12	100	12
	StDev	1.46	0.06	0.22	0.67	0.04	0.35	0.58	0.33	0.18	0.04	0.01		
High-silica mode	Mean	70.93	0.64	14.64	3.07	0.12	0.57	2.02	4.63	3.14	0.12	0.16	100	6
	StDev	2.66	0.23	1.13	0.74	0.03	0.37	0.93	0.87	0.52	0.08	0.02		
11-UW-2A-36.5 (CU1162)	Mean	74.51	0.36	13.94	1.65	0.09	0.37	1.74	4.19	2.95	0.07	0.18	100	13
	StDev	0.31	0.05	0.25	0.11	0.03	0.03	0.11	0.32	0.12	0.03	0.02		
11-UW-2-163.5 (CU1157)														
Low-silica mode	Mean	65.37	1.19	15.08	6.04	0.12	1.14	3.79	4.17	2.53	0.32	0.32	100	15
	StDev	2.72	0.60	0.80	2.40	0.07	0.54	0.94	1.04	0.51	0.23	0.13		
High-silica mode	Mean	77.36	0.29	12.84	1.33	0.04	0.28	1.05	3.27	3.29	0.03	0.26	100	6
	StDev	1.61	0.03	0.36	0.23	0.02	0.11	0.99	1.60	1.78	0.01	0.09		

11-UW-2-185 (CU1158)	Mean	76.90	0.31	12.80	1.59	0.06	0.31	1.76	4.17	1.92	0.04	0.17	100	14
	StDev	0.50	0.03	0.24	0.08	0.02	0.03	0.10	0.34	0.08	0.02	0.02		
11-UW-2-355 (CU1159)														
Low-silica mode	Mean	70.19	0.60	15.00	3.26	0.12	0.92	2.92	4.37	2.32	0.16	0.18	100	11
	StDev	0.70	0.03	0.32	0.16	0.03	0.09	0.31	0.34	0.09	0.02	0.03		
High-silica mode	Mean	75.63	0.32	13.31	1.69	0.07	0.37	1.52	4.20	2.61	0.05	0.16	100	4
	StDev	0.56	0.01	0.08	0.08	0.01	0.01	0.04	0.55	0.06	0.05	0.01		
Lower Whitshed Lake														
10-WS-2-104.5 (CU1278)														
Low-silica mode	Mean	60.26	1.15	15.94	7.45	0.22	2.63	5.81	4.26	1.88	0.29	0.13	100	15
	StDev	1.45	0.06	0.25	0.73	0.04	0.36	0.59	0.50	0.24	0.04	0.04		
High-silica mode	Mean	76.64	0.23	12.80	1.11	0.09	0.21	1.19	4.32	3.25	0.04	0.15	100	3
	StDev	0.27	0.01	0.16	0.01	0.03	0.01	0.09	0.43	0.07	0.20	0.01		
10-WS-2-127.5 (CU1149)	Mean	74.55	0.33	13.90	1.55	0.08	0.38	1.64	4.33	3.05	0.06	0.16	100	15
	StDev	0.43	0.02	0.31	0.07	0.02	0.02	0.09	0.44	0.09	0.03	0.03		
10-WS-2-189 (CU1150)														
Low-silica mode	Mean	63.36	0.92	15.81	5.51	0.31	2.50	4.57	4.02	2.12	0.72	0.21	100	3
	StDev	5.36	0.47	0.62	3.50	0.19	2.40	1.48	0.31	0.89	0.74	0.03		
High-silica mode	Mean	76.85	0.32	12.71	1.40	0.05	0.13	0.76	3.32	4.24	0.06	0.21	100	18
	StDev	1.28	0.16	0.58	0.30	0.02	0.08	0.45	0.68	1.20	0.07	0.11		
10-WS-2-198.5 (CU1151)	Mean	76.91	0.29	12.62	1.49	0.04	0.33	1.84	4.34	1.94	0.04	0.19	100	15
	StDev	0.36	0.03	0.31	0.08	0.02	0.02	0.15	0.44	0.04	0.02	0.02		

 a Samples are listed in order of age (within each lake) with youngest at top b FeOt is total iron oxide as FeO

406 407 408 409

^c n = number of analyses ^dCUXXXX = Concord University sample IDs



411

412 Fig. 5. Bivariate plots of glass geochemistry (all analyses, excluding outliers) of the tephras that 413 are stratigraphically correlated between the two lakes. Plot symbols are coded such that 414 correlative tephras have the same shape and color, but data from Upper Whitshed Lake are 415 represented by filled symbols; symbols from Lower Whitshed Lake have no fill. Data are listed 416 in Table S5.



417

Fig. 6. Bivariate plots of glass geochemistry of the tephras from Upper Whitshed Lake that were
not found in Lower Whitshed Lake. Samples 11-UW-2A-2.5 and 11-UW-2A-5 are from beds of
disseminated cryptotephra. Complete data and additional plots are included in Table S5.

421

422 *3.5. Improved tephra-matched age models*

423 Four tephras were correlated between the sedimentary sequences of Upper and Lower

424 Whitshed Lakes (refer to section 3.4), and the independently derived age estimates of these

425 tephras agree within the 95% confidence intervals of the age models in all four cases (Table 2).

- 426 These correlations were used to select age-depth model iterations from the *Bacon* output in
- 427 which the ages of all four tephra differed by less than 25 years when compared between the two
- 428 lakes. The *Bacon* output includes over 4000 ensemble members for each lake, each of which

represents a unique fit to the probability density functions of the calibration of the ¹⁴C ages for each lake. This yielded over 17 million possible permutations of the outputs from both lakes, and only 663 permutations (365 unique iterations from Upper Whitshed Lake, and 394 unique iterations from Lower Whitshed Lake) met the criteria of predicting the ages of all four of correlated tephra to be no more than 25 years apart in the two lakes. This subset of ensemble members comprises the primary age models for this study (Tables S6 and S7 contain the complete age estimates at 0.5 cm scale).

436 Overall, the 'tephra-matched' age models are very similar to the independent models: the 437 average absolute deviation in median age between independent models and tephra-matched 438 models is roughly 18 years for both lakes. Larger differences occur near the four tie-points. The 439 tephra-matched age models reduce the overall uncertainty range of the age models modestly (by 440 about 3%). The average width of the 95% confidence interval) decreased from 582 to 567 years, 441 and from 416 to 398 years in Upper and Lower Whitshed Lakes, respectively (Table 4). 442 For each of the four tephras that were correlated between the two lakes, a single best-age 443 estimate was calculated using the combined outputs of the age models for both lakes. All 758 444 model iterations that met the criteria were combined and used to calculate the median and 95% 445 confidence intervals for the four tephras. This reduced the width of the 95% confidence intervals 446 of these tephras by 33% on average compared to the independent age models from the two lakes 447 (Table 2). The combined ages are used for the four tephras for the remainder of the study.

448

449 **Table 4**

450 Comparison of different tephra matching criteria and the resulting age uncertainty for each lake, 451 and for the four tephras correlated between the lakes.

452

Tephra- match criterion (years)	# of matched permutations ^a	# of Upper Whitshed iterations	# of Lower Whitshed iterations	Upper Whitshed average 95% confidence range (years)	Lower Whitshed average 95% confidence range (years)	Average 95% confidence range for correlated tephra (years)
Independent	-	4129	4118	582	416	420
15	90	84	83	565	409	259
25	663	365	394	567	398	284
50	11933	1295	1867	561	402	324
100	205541	2828	3752	563	405	400

453

^a out of 17,003,222 permutations

454

455 **4. Discussion**

456 *4.1.* Advantages and limitations of tephra-matched age models

457 The tephra and stratigraphic correlations between Upper and Lower Whitshed Lakes show 458 that the radiocarbon-based age models are in good agreement. The novel approach in this study 459 used the output of a Bayesian, Monte Carlo-based age-modeling routine (Bacon) to synchronize 460 and further constrain the age models by selecting the individual ensemble members that show 461 reasonable agreement between the two sedimentary sequences. This method could be applied to 462 any sequences with well-correlated marker beds; however, some overlap between the confidence 463 intervals of the ages of correlated markers is needed to generate a sufficient number of iterations 464 with matched ages. Here we have synchronized two sequences, but the same technique could be 465 used with multiple records. A potential source of error in this technique is correlating events that 466 appear to be synchronous, but actually are not. One example would be correlating tephra material 467 that is geochemically similar but might be from different eruptions of the same volcanic system. 468 In this study, the distinct spacing and magnitude of the MS profile in conjunction with the 469 relatively well-dated sequences make the likelihood of such an error low.

470 The uncertainty ranges of ages produced by this method depend somewhat on the cut-off 471 value used to select the runs (i.e. the matching criterion). The sensitivity of the resulting age 472 uncertainty to the choice of matching criterion was assessed by culling the age-model ensemble 473 using different cut-off values. The results show that the matching-criterion value has a small 474 impact on the overall uncertainty of the age models, and that using broader matching criteria can 475 unexpectedly result in a slightly narrower average confidence interval (Table 4). This result can 476 be explained by the reduced weight of outlying age estimates when a greater number of iterations 477 are included in the ensemble. The age uncertainties for the correlated tephras are more strongly 478 dependent on the choice of matching criterion and therefore are not strictly objective. In this 479 study, iterations with predicted ages of the correlated tephras that were less than 25 years apart 480 between the two lakes were selected for the tephra-matched age model. This cut-off was chosen 481 as a compromise between the competing goals of matching the age models as closely as possible, 482 while not being so restrictive that the number of acceptable iterations would be too small for a 483 robust estimate of the 95% confidence interval. While a longer run time could generate more 484 age-depth iterations, and the potential to use a more restrictive matching criterion, 25 years is 485 represented by about 0.5 cm of sediment on average for Unit 1 in Lower Whitshed Lake, which is near the limit of the accuracy of the depth scales for our core samples. Like all age-modeling 486 487 routines, the selection of the goodness-of-fit criterion is somewhat subjective and dependent on 488 what the data allow. This method ensures that the two records are synchronized at four different 489 tie-points, but beyond those depths it is not possible to ascertain to what degree the age models 490 agree or diverge.

491 The tephra-matched age models improve on the independently produced age models by492 integrating geochronological information from more than one site. This is supported by

493 correlations between biogenic silica (BSi) records (Zander, 2015) from the two lakes (Fig. 7 and 494 8). An average correlation coefficient of 0.38 was calculated for the BSi records of the two lakes 495 using the 365 tephra-matched iterations from Upper Whitshed Lake and a random selection of 496 365 iterations from the Lower Whitshed Lake tephra-matched model. This improves upon the 497 0.34 average correlation coefficient calculated using 365 randomly selected iterations from the 498 independent age models. Although the difference is small, it is significant (p < 0.0001) based on 499 a t-test.





Fig. 7. Frequency of the correlation coefficients between the biogenic silica (BSi) time series from Upper and Lower Whitshed Lakes calculated for 365 age-ensemble members (details on the BSi data are in Zander, 2015). Blue and red bars compare the independent age-model outputs with the tephra-matched outputs, respectively. The tephra-matched age models tend to yield better correlations between the BSi records of the two lakes.

507

The tephra-matching method used in this study could potentially be improved through more complete integration into the Bayesian process of the *Bacon* modeling software. The *ad hoc* method used in this study reduces the number of members from the age ensemble, and cannot inform the estimates of parameters in the models, thus losing the possibility of incorporating Bayesian learning in the estimates of the distribution of sedimentation rates and their autocorrelation. Nevertheless, given the small changes to the age model overall, the differences between our *ad hoc* method and formal integration are likely negligible.

515

516 *4.2. Tephras*

Correlating tephras between sedimentary sequences requires multiple criteria, none of which 517 518 alone is absolutely conclusive. By using MS profiles, physical characteristics and major-oxide 519 geochemistry, correlations can be made with reasonable confidence, but many challenges exist. 520 Of the 11 beds sampled for geochemical analysis, only four were visible on the core face. The 521 use of crypotephra increases the potential to incorporate material from multiple eruptions, 522 including reworked tephra grains, and therefore may introduce greater uncertainty, especially 523 when the number of recovered grains is small. Several of the samples from the Whitshed Lakes 524 exhibit widely scattered geochemical data, which casts some uncertainty on the geochemical 525 correlations. For instance, 11-UW-2-163.5 (CU1157, 5863 \pm 229 BP) and 10-WS-2-189 526 (CU1150, 5498 \pm 291 BP) contain scattered geochemical data without a strong similarity 527 coefficient. Both samples contain a low-silica mode (59-69% silica) and high-silica mode (75-528 80% silica). Primarily lower-silica grains were measured from 11-UW-2-163.5, and primarily higher-silica grains were measured in 10-WS-2-189. Despite these differences, the geochemical 529

530 data overlap (Fig. 5), and do not rule out the correlation of these samples based on the unique 531 and distinctive MS profiles found in the cores from both the Whitshed Lakes (Fig. 8). 532 These samples highlight some of the challenges that accompany the use of crytotephra for 533 tephrochronological studies. The discrepancies in geochemistry we found in these samples could 534 be caused by one of the following possible reasons. (1) Stratification of the composition of a 535 disseminated tephra deposit within several centimeters of sediment, which would not be fully 536 captured by our 1-cm-thick samples centered on the highest MS value. (2) Different depositional 537 conditions at the core sites of the two lakes (e.g. differing flow regimes affecting sorting by 538 particle size or density). (3) Fractionation effects when preparing tephra samples for analysis 539 (e.g. during heavy liquid separation), or sampling bias in the selection of grains to analyze. (4) 540 The samples contain tephra from multiple eruptions, which are represented in different 541 proportions at the two lakes. If this is the case, it does not necessarily mean that it is incorrect to 542 consider these depths as time synchronous. The spikes in MS mark zones of higher 543 concentrations of tephra and possibly other minerogenic material within the sediment. Even if 544 the tephra grains are reworked, an event such as a flood or earthquake could have caused the 545 deposition of these layers of higher MS at the same time in both lakes.





Fig. 8. Example of synchronization using tephra-matching techniques for two proxy time series over the time period 4000-8000 cal yr BP. (A) Biogenic silica (BSi) data from both lakes plotted using ages derived from the independent age models. (B) The same BSi data plotted using the tephra-matched age models. (C) Magnetic susceptibility (MS) data from both lakes plotted using the independent age models. (D) The same MS data plotted using the tephra-matched age models. (D) The same MS data plotted using the tephra-matched age models. These spikes in MS represent zones of disseminated cryptotephra that are assumed to be time equivalent (samples 10-WS-2-189, 11-UW-2-163.5, 10-WS-2-198.5 and 11-UW-2-2-185).

The fact that every tephra found in Lower Whitshed Lake was also found in Upper Whitshed Lake provides some confidence that MS spikes provide a reliable indicator of tephra in our study lakes. Two tephra samples may correlate with samples taken from Cabin Lake (Zander et al., 2013), just 26 km away; however, the 95% confidence intervals do not overlap, suggesting either an age bias, or multiple eruptions with very similar geochemistry. If there is an age bias, the Cabin Lake chronology is more likely to be in error because the age models from the Whitshed Lakes yield overlapping ages for each correlated tephra.

562 Two samples were taken from depths without major MS spikes, with the goal of locating 563 tephra from the 1912 CE eruption of Novarupta, which could be a useful time marker. Payne and 564 Symeonakis (2012) suggest the Cordova area likely received distal tephra fallout from the 565 eruption, but this fallout would not have been of significant thickness as the source is about 570 566 km away. The sample (11-UW-2A-5) closest in age to this eruption yielded only a single grain of 1912 Novarupta-like composition. Similarly, MS failed to locate tephra from this eruption at 567 568 Cabin Lake (Zander et al., 2013). Novarupta ash has not yet been detected in the near-surface 569 sediment from three lakes with high sedimentation rates in the Cook Inlet region, much closer to 570 the source volcano (Boes et al., in press). Additional non-visible tephra deposits that are not 571 represented by a prominent MS peak are likely present in the Whitshed Lake cores, as indicated 572 by the presence of numerous shards in sample 11-UW-2A-2.5, which was taken from an area of 573 relatively low MS. MS is a useful tool for locating tephra deposits (de Fontaine et al., 2007), but 574 even in sediments with very low background MS, it is possible for tephra material to be 575 undetected by MS.

576 Overall, the glass chemistries are indicative of AAAP (Type I) sources (Fig. S2). Attribution 577 to specific eruptions from individual volcanoes is more difficult due to ambiguities in ages,

578 similarities in composition between multiple events from the same source, and incomplete 579 proximal eruption records. On the basis of the geochemical criteria presented by Zander et al. 580 (2013), samples 11-UW-2-185 and 10-WS-2-198.5 are most likely from Augustine volcano, 581 although the specific eruption is unclear. Samples 11-UW-2A-13 and 10-WS-2-104.5 contain 582 andesitic glass that is geochemically similar to material erupted from Crater Peak on Mount 583 Spurr (the only Cook Inlet volcano known to produce andesitic glass). However, the SC values 584 make this source determination somewhat uncertain (SC = 0.80 when these samples are 585 compared to Crater Peak 1953 sample AT252A, USGS Alaska Tephra Lab; Zander et al., 2013). 586 The beds represented by 11-UW-2A-36.5 and 10-WS-2-127.5 and by 11-UW-2-355 have 587 chemistries suggestive of Redoubt or Iliamna volcanoes, but it is not possible to refine this 588 further without additional data. The rest of the samples are from unidentified AAAP sources. 589 Tephra deposits in lakes constitute important records of volcanic events, their ages, and their 590 distribution, in part because lacustrine tephra deposits have much greater preservation potential 591 than proximal deposits on volcano slopes and because age modeling of lacustrine sequences can 592 provide robust tephra ages. The tephrostratigraphy from the Whitshed Lakes (in conjunction with 593 Cabin Lake) will provide a framework for those emerging from other lake and marine sediments 594 in the region, and as the number of records increases, our understanding of the volcanic events 595 will improve.

596

597 **5. Summary and Conclusions**

598 Seven tephra deposits were located in Upper Whitshed Lake, and four in Lower Whitshed 599 Lake. Four tephras were correlated between the lakes using the stratigraphic position and 600 magnitude of MS peaks, major-oxide glass geochemistry, and ages derived from radiocarbon

601 samples. Bayesian age models were produced for each lake using the program *Bacon 2.2* and 602 were based primarily on radiocarbon ages and supplemented by radioisotope profiles in the 603 upper most portions of the stratigraphic sequences. The correlated tephras show that the 604 independent radiocarbon-based age models for the two lakes are in close agreement because the

- 605 95% confidence intervals overlap for all four correlated markers.
- A novel approach was used to synchronize the two records using four correlated tephras.
- 607 MATLAB code was developed to select those ensemble members from the *Bacon* model output
- 608 with age estimates of the correlated tephra that agree within 25 years. This method narrowed the
- 609 confidence intervals of the age models by about 3%, and strengthened the best age estimate for
- 610 the four correlated tephras. This technique may be useful for other studies that aim to
- 611 synchronize multiple dated records with confident stratigraphic correlations. The ages and
- 612 compositions of the tephras reported here contribute to the regional tephrochronology and will be
- 613 useful for future studies of similar aged deposits in the region.
- 614

615 Supporting Information

- 616 Additional supporting information can be found in the online version of this article:
- 617 <u>https://doi.org/10.1016/j.quageo.2018.01.005</u>
- Table S1: ²¹⁰Pb, ¹³⁷Cs and ²⁴¹Am profiles from Upper Whitshed Lake
- 619 Table S2: ²³⁹⁺²⁴⁰Pu profiles from Upper and Lower Whitshed Lakes
- 620 Table S3: Upper Whitshed age model inputs
- Table S4: Lower Whitshed age model inputs
- Table S5: Complete analytical data on Whitshed Lakes tephra samples
- 623 Table S6: Upper Whitshed age model output

- 625 Fig. S1: Tephra source differentiation reference data
- 626 Fig. S2: Tephra source differentiation Whitshed Lake data
- 627 Fig. S3: Independent age-model for Upper Whitshed Lake
- 628 Fig. S4: Independent age-model for Lower Whitshed Lake
- 629 Appendix: Tephra matching source code
- 630

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