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New occurrences of the White River Ash (east lobe) in Subarctic Canada and utility for estimating freshwater reservoir effect in lake sediment archives

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ABSTRACT

The freshwater reservoir effect (FRE) in the Canadian Subarctic complicates development of high-resolution age-depth models based on radiocarbon dates from lake sediments. Volcanic ashfall layers (tephras) provide chronostratigraphic markers that can be used to estimate age offsets. We describe the first recorded occurrence of a visible tephra in a lacustrine sequence in the central Northwest Territories. The tephra, observed in Pocket Lake, near Yellowknife, is geochemically and stratigraphically attributed to the White River Ash east lobe (WRAe; 833–850 CE; 1117–1100 cal BP), which originated from an eruption of Mount Churchill, Alaska. We also observed the WRAe as a cryptotephra in Bridge Lake, 130 km to the NE, suggesting that records of this tephra are potentially widespread in CNT lakes. The identification of this tephra presents opportunities for use of the WRAe as a dating tool in the region and to quantify the magnitude of the FRE in order to correct radiocarbon age-depth models. Two well-dated sediment cores from Pocket Lake, containing a visible WRAe record, indicate a FRE of ~200 years at the time of the ash deposition, which matches closely with the estimated FRE of ~245 years at the lake sediment-water interface. Although additional results from other lakes in the region are required, this finding implies that FRE estimates for the late Holocene in the region, may be based either on down-core WRAe/radiocarbon age model offsets, or on radiocarbon dates obtained from the sediment-water interface.

1. Introduction

The central Northwest Territories region of Canada has abundant lakes with well-preserved sediments that archive continuous records of postglacial Holocene climate variability (Crann et al., 2015). A critical component of any paleoclimate study in the region is the development of reliable age-depth models, which are principally reliant on radiocarbon dating (Wright et al., 2017). Radiocarbon dating of sedimentary cores can be carried out on a variety of materials including terrestrial-derived plant macrofossils, aquatic derived plant macrofossils, and pollen grains. Due to a general lack of suitable macrofossil material for dating in lake sediments within the barren northern landscapes, bulk organic samples are typically chosen for radiocarbon dating out of necessity (Oswald et al., 2005; Crann et al., 2015; Zhou et al., 2015). If bulk sediments have a large component of submerged aquatic organic material, old organic material, or material derived from carbonate bedrock washed in from the catchment at the time that the sediment is deposited, there will be an offset between the radiocarbon content of the contemporaneous atmosphere and the measured radiocarbon content of the bulk sample. This offset is known as the freshwater reservoir effect (FRE). The occurrence and magnitude of the FRE can vary on a lake-to-lake basis, and if the FRE cannot be closely estimated, the useful resolution of age-depth models is reduced (Abbott and Stafford, 1996; Lowe et al., 1997; Newnham et al., 1998).

Observation of a white ~3 to 5-mm-thick depositional unit in two freeze cores from Pocket Lake (<4 ha), located within the city limits of Yellowknife, Northwest Territories, suggested that there may be a tephra deposit, which would be the first reported visible occurrence of a

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tephra from a lacustrine environment in the central Northwest Territories. Plinian-type volcanic eruptions are often associated with copious ash production that may be distributed by winds across a broad geographic area (Walker and Croasdale, 1971). The resultant ash layers, known as tephra, provide isochronous stratigraphic horizons useful for correlation within disparate depositional environments, particularly lake and bogs (Lowe, 2011). In northwestern North America, there have been many Plinian-type volcanic eruptions through the Holocene (Pyne-O'Donnell et al., 2012). Based on the stratigraphic positioning of these white deposits and an existing skeleton age-depth model, it was hypothesized that the Pocket Lake tephra layers may correlate with the White River Ash east lobe (WRAe; 833–850 CE), which originated from a massive rhyodacite Plinian eruption of Mt. Churchill, Alaska (West and Donaldson, 2002). At other locations, visible evidence of the ash varies in thickness from 0.5 m near the source of the eruption at Mt. Churchill, thinning exponentially to mm-scale occurrences in distal regions west of Great Slave Lake (Lerbekmo, 2008; Robinson, 2001). Depositional and grain size analysis indicate that the eruptive plume was 40–45 km in height and was distributed by ~10 m/s winds that were sustained at this velocity for ~2 days (Lerbekmo, 2008). The presence of the WRAe as a cryptotephra was also recently recognized in Maine, Nova Scotia, and Newfoundland (Jensen et al., 2014; Mackay et al., 2016; Pyne-O'Donnell et al., 2012). Geochemical and morphological evidence has also shown that the WRAe correlates with the "AD860B" ash (846–848 CE) found in Greenland and northern Europe (Jensen et al., 2014). There have been no reports of the WRAe from anywhere within the intervening expanse of the Canadian north. The elongate east-west orientation of the WRAe lobe indicates that strong eastward blowing winds prevailed during the eruption (West and Donaldson, 2002). As the high atmospheric wind patterns over Alaska trend eastward in the winter and northward in the summer, it has been concluded that the WRAe was likely deposited during the winter months (West and Donaldson, 2002). This raises the possibility of the WRAe being a widespread, but undocumented visible tephra and/or cryptotephra marker throughout the Canadian north. Recognition of the WRAe in Pocket Lake would represent a first step in this process by extending the visible occurrence of the tephra > 100 km further east than previously reported (Robinson, 2001; Lerbekmo, 2008; Fig. 1).

Refining our understanding of the aerial extent, dynamics, and temporal distribution of the WRAe and other tephra depositional events across Northwestern Canada, in particular such studies inform on the risk associated with long-range ash dispersal from northern Pacific Arc volcanoes (Bourne et al., 2016). For example, the relatively small volume tephra cloud derived from the 2010 eruption of the Icelandic volcano Eyjafjallökull caused major European air travel disruptions that cost the global economy billions of dollars (Swindles et al., 2011, 2013). Most recently the March 2016 eruption of Pavlof volcano on the Alaska Peninsula sent a plume 11,000 m into the atmosphere, draping areas downwind in ash, and forcing the temporary cancellation of flights between Yellowknife, Regina and Edmonton, >3000 km downwind (Bourne et al., 2016; Canadian Press, 2016).

Subarctic Canada is also a 'canary in a coal mine' for understanding climate change, which has occurred more rapidly in northern regions than at lower latitudes (Delworth et al., 2016). Being able to understand the nature of previous climate variability is a key part of ongoing research. Critical to this research are good age models, which rely on having a better understanding of reservoir effect in the region, and simply alerting researchers that cryptotephra chrono-markers are even present in this vast region is important (Lowe et al., 1997; Lowe, 2011).

The most accurate down-core estimates of FREs are derived from sedimentary units deposited during a known time frame, with tephra layers being the most widely used comparative chronostratigraphic markers (MacDonald et al., 1991). Confirmation that the observed tephra layer is the WRAe would be a significant contribution to the development of accurate age models for this region, providing geochronologists with an additional chronostratigraphic marker.

The purpose of this research was to: 1) determine if the thin tephra units observed in the Pocket Lake cores could be correlated with the WRAe using its stratigraphic, physical and geochemical properties and, if so, use the known age of the WRAe to estimate an absolute FRE for Pocket Lake; 2) compare the FRE obtained for the tephra against the value obtained from the sediment-water interface to determine the nature of any late Holocene FRE variability; 3) determine if the WRAe could be identified in another lake in the region (Bridge Lake) as a cryptotephra and, if so, use the WRAe to characterize the FRE and again compare the downcore FRE to the estimate at the sediment-water interface. This contribution also adds novel textural, compositional, environmental and applied use of the WRA ash, a tephra that has a long history of academic enquiry and continued relevance as a rather recent and large volcanic eruption (Jensen et al., 2014).

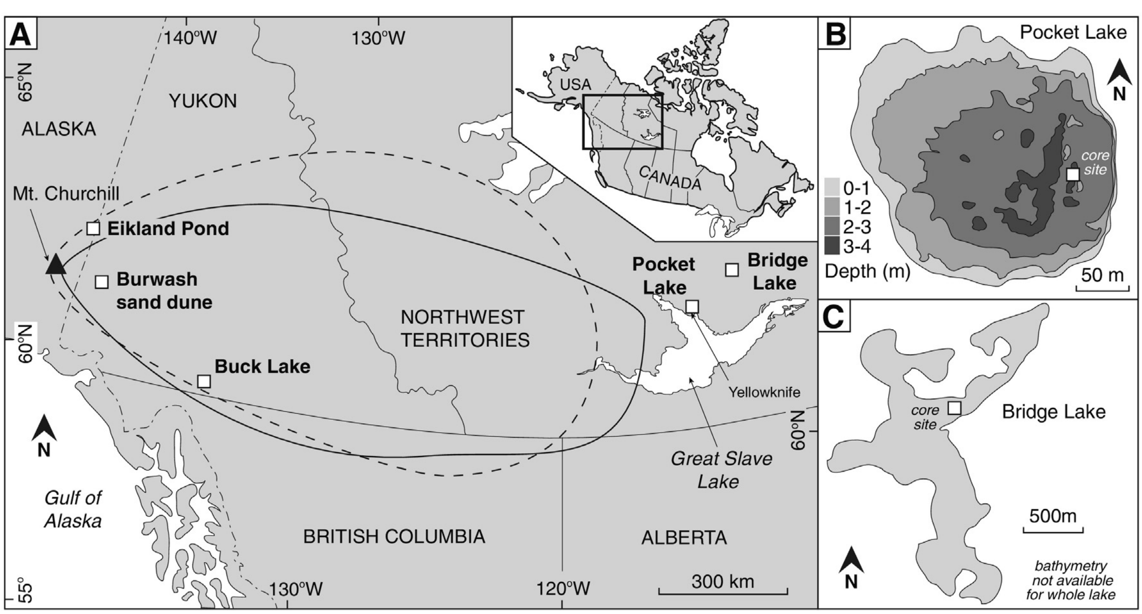

Fig. 1. (A) Map showing locations of study sites (squares) in relation to the extent of the White River Ash after Leberkmo (2008; dashed line) and Robinson (2001; solid line). Inset shows location of study area within Canada and Alaska. (B) Outline of Pocket Lake showing bathymetry and coring location. (C) Outline of Bridge Lake and coring location.

2. Methods

2.1. Core collection

Two freeze cores (PKT_1FR and PKT_2FR) were collected <3 m apart from Pocket Lake in March 2012 at a water depth of 3.5 m (Fig. 1). Core Pocket_1F was determined in the field to have over-penetrated the lake bottom sediment-water interface by several centimeters. Both cores were transported frozen to Carleton University for subsequent analysis. During stratigraphic logging both cores were observed to contain a wispy, white tephra layer < 5 mm thick at 55–56 cm in PKT_2FRF1, and 35–36 cm in PKT_1F.

The cores were subsampled using a custom designed sledge microtome (Macumber et al., 2011) and in each the tephra layer was further isolated in distilled water and gently agitated to isolate any remaining organic material. Visual inspection of the samples under a dissecting microscope confirmed that they were comprised of clear, blocky, glass shards.

2.2. Physical characterization of shards

Based on a literature search of known tephras in northwestern North America (e.g. Clague et al., 1995; Lerbekmo, 2008; Robinson, 2001), radiocarbon age models, and stratigraphic position of the ash layers in the cores, we surmised that the observed tephra layers were most likely attributable to the WRAe. To geochemically confirm the identity of the Pocket Lake tephra we obtained for analysis known WRAe samples from Eikland Pond (62°19′16″N; 140°49′03″W), Buck Lake (60°18′10″ N, 134°46′09″W), and Burwash Dune (61°20′00″N, 139°23′00″W), all located from 110 to 390 km from the Mt. Churchill eruption site (Fig. 1).

Tephra-derived glass from each locality described above was examined using transmitted-light microscopy and digital back-scattered electron (BSE) imagery (Fig. 2). Digital BSE images were obtained with an Electron Optic Services digital imaging system at 512 × 512 pixel resolution with a Lamont 4 element solid state BSE detector and BSE Quad Summing Amplifier interfaced to a 4Pi Analysis Inc. digital imaging and EDX X-ray system at Carleton University. The shards were then visually categorized into four morphologies: (1) frothy; (2) fibrous; (3) bubble-wall stretched; and (4) platy (after Ross, 1928; Heiken, 1972; Yoshikawa, 1976).

2.3. Major element chemistry

Major element oxides were analyzed with an automated 4 spectrometer Cameca Camebax MBX electron probe by wavelength dispersive X-ray analysis at Carleton University (Table 1). Operating conditions of the microprobe were 15 kV accelerating potential and a beam current of 15 nA. Volcanic glass shards were analyzed using a rastered electron beam 8 × 8 μm in size. Peak counting times for analyzed elements were 10–30 s or 40,000 accumulated X-ray counts. Background measurements were made at 50% peak counting time on each side of the analyzed peak. Raw X-ray data were converted to normalized weight % using a Cameca PAP matrix correction program. Natural and synthetic minerals were used as calibration standards and a number of secondary internal reference standards were routinely measured with the glass samples (as recommended by Kuehn et al., 2011; Lowe, 2011). Elements analyzed and standards employed were: Na-albite; K-microcline USNM; Ca-wollastonite; Al-spinel; Si,Mg-olivine; Ti,Mn- synthetic $MNTiO_3$; Cr-synthetic Cr_2O_3; Fe-synthetic fayalite; Cl-tugtupite; P- beryllonite; Ba,S-barite; F-synthetic LiF. The reference

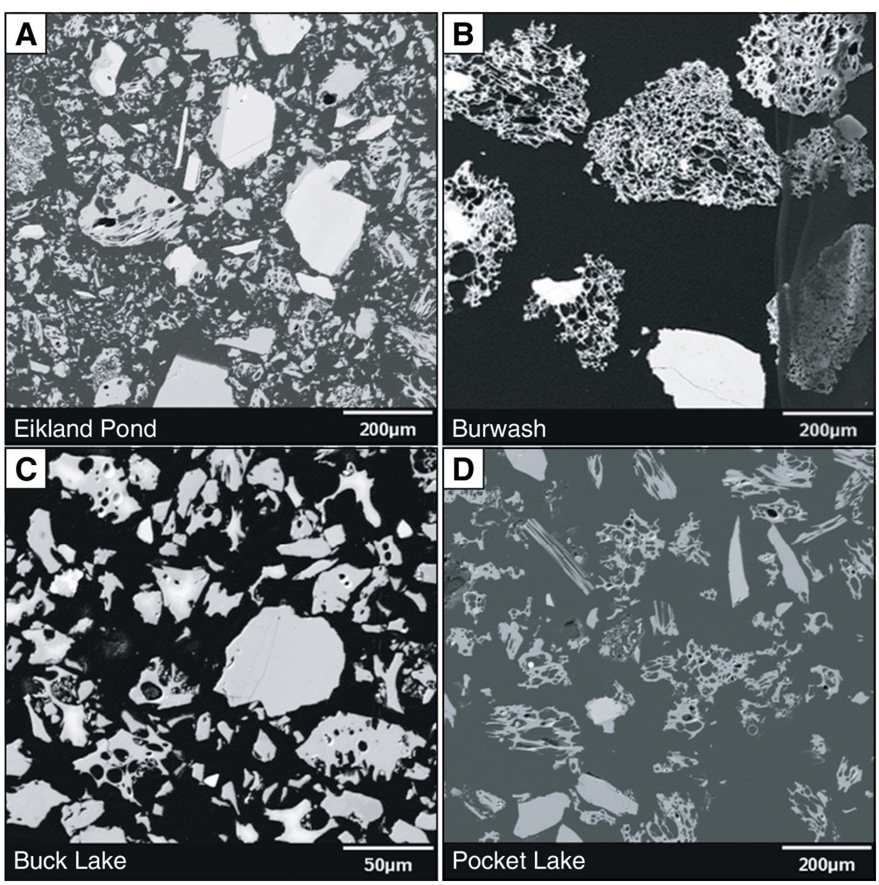

Fig. 2. Electron microprobe derived images of glass shards from each site (A. Eikland Pond; B. Burwash; C. Buck Lake; D. Pocket Lake). Both Pocket Lake and Burwash Dune samples are characterized by vesicles with similar properties, and shards displaying a frothy, fibrous and platy morphology. Shards from Pocket Lake were morphologically distinct from the frothy and fibrous shards from Eikland Pond, and the frothy, bubble-walled, stretched and platy tephra from Buck Lake.

Table 1
Average major oxide concentrations for glass shards from localities analyzed. Results are normalized to 100%. Standard deviation shown in right column.

	Eikland Pond		Burwash Dune		Buck Lake		Pocket Lake	
SiO_2	75.85	±1.04	75.57	±1.23	75.22	±1.35	75.36	±1.14
Al_2O_3	13.97	±0.32	13.86	±0.52	14.23	±0.82	14.51	±0.3
TiO_2	0.17	±0.07	0.16	±0.06	0.17	±0.03	0.18	±0.06
Cr_2O_3	0.02	±0.05	0	±0.01	0.01	±0.01	0.01	±0.01
FeO	1.21	±0.15	1.29	±0.3	1.26	±0.18	1.49	±0.14
MnO	0.06	±0.02	0.05	±0.02	0.05	±0.03	0.05	±0.02
MgO	0.27	±0.06	0.27	±0.09	0.24	±0.07	0.38	±0.04
Na_2O	2.95	±0.68	3.2	±0.68	3.71	±0.38	2.57	±0.84
K_2O	3.45	±0.28	3.4	±0.22	3.05	±0.2	3.03	±0.22
CaO	1.54	±0.14	1.59	±0.22	1.61	±0.36	1.84	±0.14
BaO	0.09	±0.06	0.16	±0.07	0.11	±0.03	0.16	±0.06
P_2O_5	0.03	±0.02	0.04	±0.03	0.02	±0.01	0.04	±0.02
SO_3	0.01	±0.01	0.01	±0.01	0.02	±0.01	0.01	±0.02
Cl	0.32	±0.03	0.32	±0.03	0.26	±0.04	0.3	±0.04
F	0.06	±0.06	0.06	±0.05	0.04	±0.03	0.09	±0.09
No. of shards	15		16		14		37	

Results are normalized to 100%. Standard deviation shown in right column.

standards were: KK1 kaersutite (Reay et al., 1989), basaltic glass VG-2 (USNM111240/52), Yellowstone rhyolite glass VG-568 (USNM7285), and Dow Corning synthetic glass tektite (USNM2213) (Supplementary data table 1).

2.4. Identification of tephra elsewhere in region

To determine if WRAe tephras could be identified in other lakes where ash layers were not visible, sediments from freeze core ROAD-BRIDGE2, collected from Bridge Lake in March 2010 at a water depth of 4.5 m, were analyzed for the presence of cryptotephra. Samples were extracted at 1 cm intervals through the entire Bridge Lake core and prepared for analysis following a modified version of the method presented in Swindles et al. (2010). After the samples were burnt in a muffle furnace, 10% HCl was added to remove carbonate and the samples were sieved using a 63 μm sieve to separate minerogenic material. Glass shards > 63 μm were observed through the 10–17 cm interval of the core, being most abundant within the 14–15 cm interval, and counted under high power microscopy.

2.5. Radiocarbon dating and age-depth modeling

Bulk sediment samples were used for radiocarbon dating since macrofossils are absent and the sediment is homogeneous throughout the Pocket and Bridge lake cores (Tables 2,3). All samples were radiocarbon dated by accelerator mass spectrometer either at the ^{14}CHRONO Dating Laboratory in Belfast, Northern Ireland (Lab ID "UBA") or at the Lalonde AMS Laboratory in Ottawa, Canada (Lab ID "UOC"). Samples were pretreated with a standard hydrochloric acid wash to remove carbonate material. In a test to determine whether the humic acid component was mobile and thus contributing to the FRE, a subset of samples from Pocket Lake (UOC-654, UOC-656, UOC-733, UOC-734) underwent acid-alkali-acid (AAA) pretreatment, which involves removing the humic component during the alkali step using NaOH, followed by an acid wash to remove any CO_2 that may have been absorbed during the base wash (Crann et al., in press). Aliquots from the same depth horizons were pretreated with the acid wash only and the results show no pattern, nor real statistical difference. Radiocarbon ages were calibrated using OxCal v4.2 (Bronk Ramsey, 2009) and the IntCal13 calibration curve (Reimer et al., 2013). The age-depth models were created using the age modeling software Bacon version 2.2 (Blaauw and Christen, 2011, 2013) and the IntCal13 calibration curve (Reimer et al., 2013). The modeling parameters for accumulation rate and memory are based on values for lakes (Crann et al., 2015). The age model results confirm that the 20 cm offset in the occurrence of the tephra in the two cores (55–56 cm [PKT_2FRF1]; 35–36 cm [PKT_1F]) was due to the over penetration during collection of PKT_1F.

3. Results

3.1. Glass shard morphology

Glass shard morphological variation is controlled by a complex relationship between a variety of factors, including magma composition,

Table 2
Radiocarbon dates from the two Pocket Lake cores, calibrated with the IntCal13 calibration curve (Reimer et al., 2013) using OxCal v4.2.4 (Bronk Ramsey, 2009) following conventions of Millard (2014). Bold tephra date based on wiggle-match date for WRAe (Jensen et al., 2014).

	Lab ID	Depth (cm)	^{14}C age BP ± 1σ	Pretreatment	Cal BP ± 2σ
PKT_2FRF1	UBA-20676	10–10.5	362 ± 27	Acid only	500–422 (50.7%) 400–316 (44.7%)
	UBA-22350	20–20.5	731 ± 31	Acid only	727–653 (95.4%)
	UBA-20679	52–52.5	1335 ± 25	Acid only	1302–1239 (85.5%) 1205–1186 (9.9%)
	Tephra	**55–56**			**1110 ± 50**
	UBA-22351	57–57.5	1394 ± 30	Acid only	1350–1279 (95.4%)
	UBA-22352	70–70.5	1725 ± 31	Acid only	1707–1561 (95.4%)
	UBA-20678	128.5–129	2966 ± 26	Acid only	3215–3057 (93.9%) 3049–3035 (1.3%)
PKT_1F	UBA-20680	35.5–36	795 ± 27	Acid only	674–759 (95.4%)
	Tephra	**55–56**			**1110 ± 50**
	UBA-22346	56–56.5	1401 ± 27	Acid only	1349–1285 (95.4%)
	UOC-653	60–60.5	1607 ± 29	Acid only	1555–1413 (95.4%)
	UOC-654	60–60.5	1553 ± 27	AAA	1526–1386 (95.4%)
	UBA-22347	83.5–84	2145 ± 31	Acid only	2304–2238 (24.9%) 2182–2037 (68.2%) 2025–2007 (2.4%)
	UOC-655	109–109.5	2918 ± 26	Acid only	3158–2970 (95.4%)
	UOC-656	109–109.5	2960 ± 27	AAA	3211–3007 (95.4%)
	UOC-733	109–109.5	3029 ± 19	AAA	3334–3290 (20.9%) 3257–3166(74.5%)
	UOC-734	109–109.5	3088 ± 19	AAA	3363–3241 (95.4%)
	UOC-923	140–140.5	3739 ± 27	Acid only	4221–4208 (2.0%) 4156–4061 (62.8%) 4052–3986 (30.7%)
	UOC-924	180–180.5	4254 ± 31	Acid only	4868–4813 (83.1%) 4755–4708 (12.3%)

Table 3
Radiocarbon dates from the Bridge Lake core, calibrated with the IntCal13 calibration curve (Reimer et al., 2013) using OxCal v4.2.4 (Bronk Ramsey, 2009) following convention of Millard (2014). Bold tephra date based on wiggle-match date for WRAe (Jensen et al., 2014).

	Lab ID	Depth (cm)	^{14}C age BP ± 1σ	Pretreatment	Cal BP ± 2σ
Bridge Lake R10P26	UBA-18964	6.5	28 ± 23	Acid only	252–230 (10.0%) 133–116 (6.6%) 71–34 (78.8%)
	UBA-22873	12.5	694 ± 26	Acid only	684–644 (76.5%) 588–565 (18.9%)
	Tephra	**15**			**1110 ± 50**
	UBA-18965	18	1883 ± 23	Acid only	1883–,1737 (95.4%)
	UBA-22874	24.5	3782 ± 30	Acid only	4246–4082 (93.4%) 4030–4010 (2.0%)
	UBA-22875	30.5	4730 ± 30	Acid only	5584–5500 (44.8%) 5491–5446 (20.7%) 5400–5326 (29.9%)
	UBA-22876	34.5	5487 ± 31	Acid only	6396–6370 (4.0%) 6343–6338 (0.5%) 6323–6263 (72.9%) 6251–6210 (18.0%)
	UBA-18966	41.5	5816 ± 42	Acid only	6727–6502 (95.4%)
	UBA-22877	50.5	6184 ± 32	Acid only	7174–6978 (95.4%)
	UBA-18967	59.5	6762 ± 32	Acid only	7667–7576 (95.4%)
	UBA-22878	64	7025 ± 34	Acid only	7940–7789 (95.4%)

volatile content, and the influence of external water (Heiken and Wohletz, 1985, 1991; Scasso and Carey, 2005). Examination of the glass shard morphology of tephra deposits can also yield insight into eruptive processes (e.g. Dellino and la Volpe, 1996; Dellino et al., 2005). The 'frothy, fibrous and platy' shards from Pocket Lake core 2FR-F1 bore a close resemblance to the sample from Burwash Dune (Fig. 2). Both samples have the same glass shard morphology (frothy, fibrous and platy), and vesicles displayed similar properties. This close similarity indicates that both tephra deposits originated from a similar style of volcanic eruption. The morphological correlation between the tephra from Pocket Lake and the 'frothy and fibrous' shards from Eikland Pond was less clear. There were significant differences between the tephra from Pocket Lake and the 'frothy, bubble-walled, stretched and platy' tephra from Buck Lake (Fig. 2).

3.2. Geochemical analysis

Geochemical analysis of the from Pocket Lake (2FR-F1) and the WRAe samples from Buck Lake, Burwash Dune and Eikland Pond revealed that all are geochemically similar, consistent with an origin from the same volcanic eruption (Table 1; Supplementary data table 1). Fields representing the individual analyses were plotted on a total alkali-silica plot and a K_2O-FeO_t-CaO ternary diagram, supplemented by previously published results from the summit and a proximal pumice mound of Mt. Churchill (Richter et al., 1995). On the total alkali-silica plot, the field for Pocket Lake overlaps with fields for all WRAe localities; clustering around 75–76 wt% SiO_2 and 6–7.5 wt% $Na_2O + K_2O$ (Fig. 3A). The Pocket Lake samples are characterized by marginally lower alkali concentrations than observed at the other localities. On the K_2O-FeO_t-

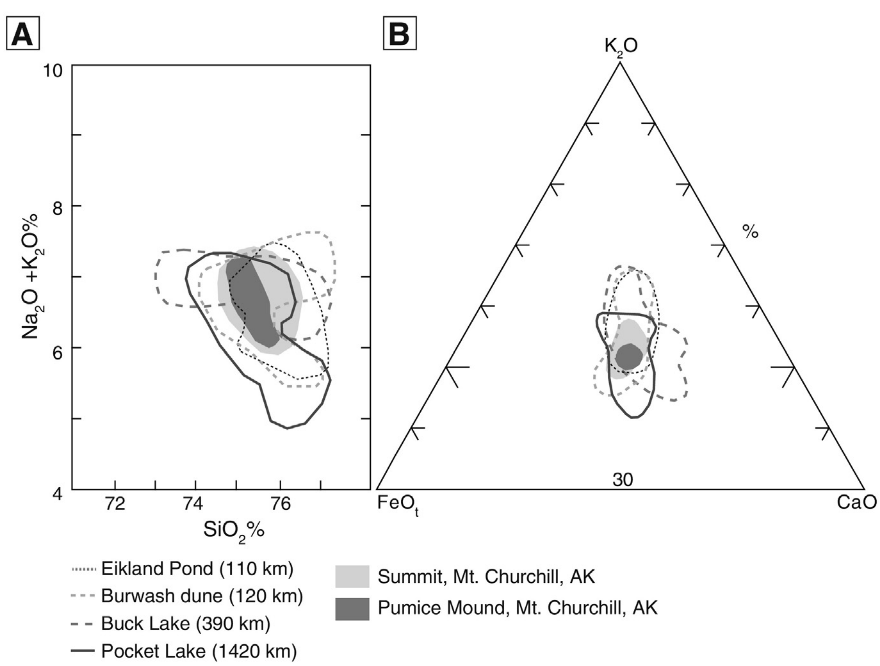

Fig. 3. Normalized analyses results plotted on (A) a total alkali-silica plot and (B) a K_2O-FeO_t-CaO ternary diagram See Table 1 for average major oxide concentration values plotted here. Shaded fields represent previously published results from the summit and a proximal pumice mound of Mt. Churchill (Richter et al., 1995).

CaO plot the samples are tightly clustered and have a decreasing relative proportion of K and increase in CaO and FeO_t with increased distance from the volcanic center (Fig. 3B). Within this tight grouping the Buck Lake and Burwash Dune samples were both characterized by higher relative CaO and FeO_t content than that at the other localities. The Pocket Lake sample plotted between Buck Lake and Burwash Dune samples in terms of relative CaO and FeO_t content, and is characterized by the lowest relative K values measured.

4. Discussion

4.1. White River Ash in the central Northwest Territories

The WRAe tephra layers visible in the Pocket Lake cores are considerably eastward of the previously mapped visible occurrences and are the first such occurrences of any kind in the central Northwest Territories (Clague et al., 1995; Robinson, 2001; Lerbekmo, 2008). The closest record of the WRAe as a visible layer is from peats ~100 km to the west, with the nearest lacustrine record being from near Wrigley, Northwest Territories, 470 km to the northwest (Robinson, 2001).

That the Mt. Churchill eruption that produced the WRAe occurred most likely during the winter (West and Donaldson, 2002), in combination with the shape of the lake, may be responsible for the visible occurrence of the tephra in Pocket Lake. As Pocket Lake is a compact, subrounded, steep-sided lake surrounded by barren bedrock, it is likely that sediment focusing played a role during accumulation of the WRAe in it (Watson et al., 2016a). Deposition of the WRAe during the winter months would have resulted in accumulation on the frozen lake surface and within the surrounding catchment area. With melting of the snowpack in the spring, ash would have been flushed into the lake and focused to deeper parts of the lake, resulting in an ash layer apparently thicker than normal for a location ~1435 km from the eruption center (Robinson, 2001; Lerbekmo, 2008).

The observation of a cryptotephra in Bridge Lake, 130 km to the NE, at the same stratigraphic horizon as the confirmed WRAe tephra layer from Pocket Lake indicates that this unit is present and potentially available for use as a stratigraphic marker in lakes throughout the region. Although the cryptotephra record in the Bridge Lake core spans the 10–17 cm interval the peak at 14 cm correlates well with the age of the WRAe (Fig. 5b). Up and down-core diffusion is common in cryptotephra records and is attributable to factors such as bioturbation and compaction (Swindles et al., 2010). Cryptotephra have as yet not been identified in peatlands in this region, which may relate to lake sediments generally containing a greater number of larger shards than peatlands (Watson et al., 2016b).

4.2. Late Holocene fresh water reservoir age determination

Recent wiggle-match dating of the WRAe by Jensen et al. (2014), based on multiple radiocarbon dates from a spruce killed by the eruption, has provided a 95% (2σ) probability date of 833–850 CE (1117–1100 cal BP). The 95% (2σ) probability dates estimated by the Bayesian age-depth model for the WRAe horizon in the Pocket Lake cores are 1310 cal BP (1240–1360 cal BP) for the core Pocket_2FR_F1 and 1300 cal BP (1230–1375 cal BP) for core Pocket_1FR. Based on the known WRAe age, both cores yield a consistent age difference of ~200 years from the known date of the eruption (Fig. 4). As there are no other known tephras near this age in northwest North America, this evidence coupled with the shard morphology and geochemical results indicate that this is an occurrence of the WRAe. We conclude that the offset between the age suggested by the WRAe and radiocarbon age model is the result of a FRE.

A common mechanism for the development of FRE conditions involves the runoff of dissolved and particulate organic carbon derived from Arctic peatlands and soils within the lake watershed. Organic matter is slow to decompose in these environments and often resides in permafrost for long periods before eventually eroding into a lake basin (MacDonald et al., 1991). The magnitude of the FRE is generally higher in environments characterized by low decomposition rates (Abbott and Stafford, 1996). As Subarctic and Arctic lake sediments tend to be characterized by low rates of productivity and decomposition, the low sedimentation rates typically found there results in the recycling of ^{14}C-depleted organic matter, making these systems particularly sensitive to inputs from sources of old carbon (Grimm et al., 2009).

Gytjja-type muds typical of northern lakes are mixing of decayed terrestrially derived organic material of uncertain origin, which produces a FRE determined entirely by local conditions (Cohen, 2003). Hard-water effects have also been shown to be a possible cause of FRE (Lowe et al., 1997; Newnham et al., 1998; Lowe, 2011). In some Arctic environments the FRE value at the sediment-water interface can be very high. For example, sediment-water interface samples dated from well above the treeline on Baffin Island, Nunavut, yielded dates of ~1000 ^{14}C year (Abbott and Stafford, 1996).

There are two methods that are commonly used to estimate FRE from terrestrially derived organic materials in lake sediments. The most obvious way to determine the magnitude of the FRE in a lake is to radiocarbon date sediments from the sediment-water interface (Abbott and Stafford, 1996). The surficial date obtained for a particular lake is then used as a correction factor by subtracting it from all ^{14}C dates obtained for a core from the lake prior to calibration (Abbott and Stafford, 1996). Yu et al. (2007) proposed an alternative method whereby a reasonable estimate of FRE could be determined by extrapolating age-depth models derived from subsurface radiocarbon dates to the surface. In addition, care must be taken when using either the top-down or bottom-up approaches outlined above as hydrological changes in a lake over time can result in changes to FRE, most closely associated with sedimentological transitions (Abbott and Stafford, 1996; Grimm et al., 2009; Zhou et al., 2015). In Pocket Lake the radiocarbon age model indicates a sediment/water interface FRE of 245 years, in line with the value of 200 years obtained using the WRAe at ~1100 cal BP In other words, the results are almost the same using both a bottom-up and top-down approach to estimating FRE for at least this lake.

In Bridge Lake the apparent lack of FRE at the sediment/water interface is difficult to compare against the down core occurrence of the WRAe cryptotephra as the age model (core ROAD-BRIDGE1) and cryptotephra (core ROAD-BRIDGE2) were derived from different, although closely spaced cores (Fig. 5). Although an apparent downcore FRE of 290 years is obtained for core ROAD-BRIDGE2 if the Baysian Age model from ROAD-BRIDGE1 is directly overlain, sedimentation rates are so slow in these northern lakes that even a subtle offset between the two cores could mean that the apparent FRE for Bridge Lake could either be significantly higher or lower than 290 years. Although an estimate of FRE is not possible with the available data the resolution is high enough to confirm that the observed cryptotephra is attributable to the WRAe.

The modern climate system became established in the central Northwest Territories by ~3300 cal BP (Patterson et al., 2004, 2011; Babalola et al., 2013) as evidenced by fairly constant sedimentation rates in regional lakes throughout this period (Crann et al., 2015). Radiocarbon dates obtained at the sediment/water interface for other lakes in the region have yielded estimates of FRE varying from 0 to 500 years with higher values consistently associated with small round lakes and consistently low values obtained from larger more irregularly shaped lakes (Crann et al., 2015). Unlike carbon isotopic composition of the atmosphere, which is well mixed, the isotopic composition of lakes are commonly subject to nonequilibrium and the varying influence of CO_2 derived from multiple sources (Cohen, 2003). As the lakes where this differential FRE are distributed throughout the central Northwest Territories, in a variety of settings, we hypothesize that the more restricted circulation typical of smaller lakes in the region may be a major contributing factor to the higher sediment-water interface FREs in these settings (Wetzel, 2001). A detailed study of these lakes is

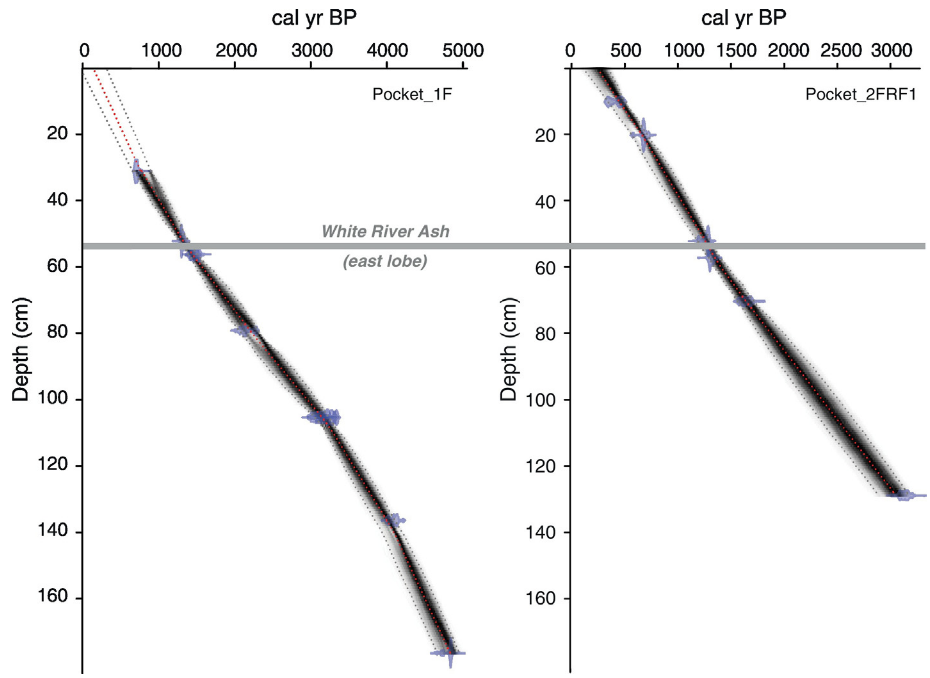

Fig. 4. Age-depth models from the two Pocket Lake cores showing the depth of the White River Ash (1110 ± 50 cal BP) and the projected surface ages. Models were created using Bacon v2.2 (Blaauw and Christen, 2011) and the IntCal13 calibration curve (Reimer et al., 2013).

required to definitively isolate the underlying causes for this apparent difference in FRE based on lake morphology. Whatever the underlying cause for the observed variation in FRE, the results from Pocket Lake suggest that apparent ^{14}C ages obtained at the sediment/water interface in lakes from the region may potentially be applied to estimate the FRE in individual lake basins through the late Holocene (ca. <3300 cal BP).

5. Conclusions

1. We present data on the first visible- and crypto-tephra layers observed in lacustrine sediments from the central Northwest Territories in the Canadian Subarctic. Analysis of shards observed in two cores obtained from Pocket Lake, Yellowknife was carried

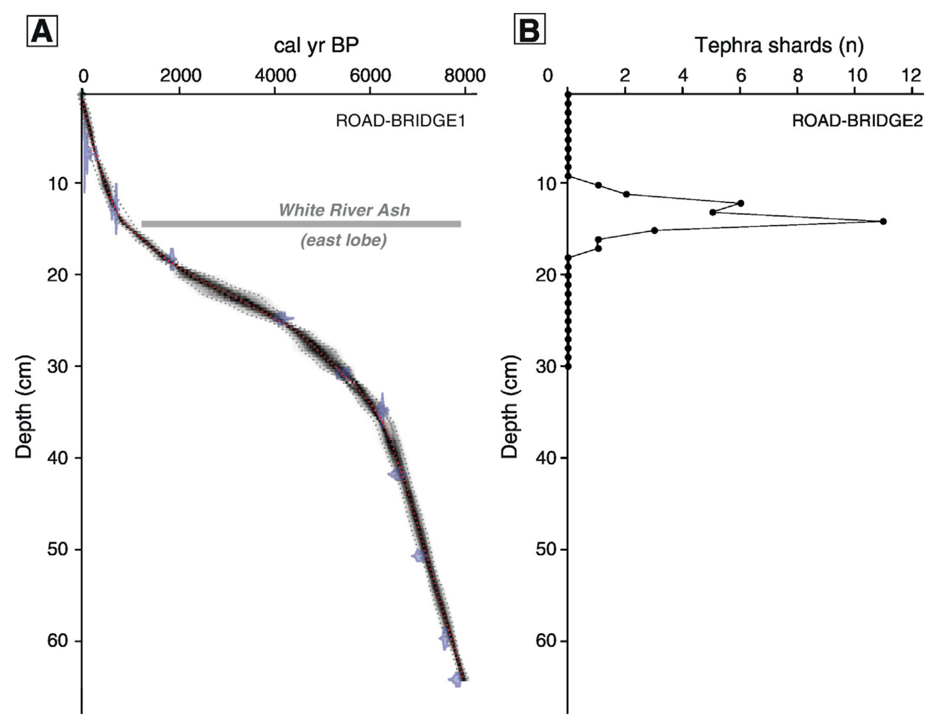

Fig. 5. (A) Age-depth model including sediment-water interface radiocarbon age of AD2010 ± 20 from core ROAD-BRIDGE1, as well as position of White River Ash (1110 ± 50 cal BP) derived from nearby core ROAD-BRIDGE2. Age-models were created using Bacon v2.2 (Blaauw and Christen, 2011) and the IntCal13 calibration curve (Reimer et al., 2013). (B) Downcore tephra shard count from nearby core ROAD-BRIDGE2. Although the tephra shards were sparse through the core, some were quite large (>80 um) and vesicular. As the age model and tephra counts were made from separate cores determination of FRE in Bridge Lake cannot be determined with accuracy in this low sedimentation rate environment, although comparison is adequate to confirm that the tephra is WRAe.

out using transmitted-light microscopy, digital back-scattered (BSE) imagery and comparative geochemical analysis. The results indicate that the glass shards are compositionally indistinguishable on the basis of major elements from those of the rhyodacite White River Ash (WRA), derived from an 833–850 CE (1117–1100 cal BP) plinian eruption of Mt. Churchill, Alaska, 1435 km to the west.

2. This occurrence of the WRAe is the farthest eastward from Mt. Churchill that the unit has been observed as a *visible* tephra layer. This occurrence, and the lack of other visible occurrences in lake cores from lakes in the region, is likely the result of depositional-focusing within the restricted Pocket Lake catchment and basin.
3. The ~200 year offset observed between the WRA and the radiocarbon age models derived from both Pocket Lake cores provides an independent confirmation of FRE, and confirmation that the phenomenon is present within the stratigraphic record.
4. The discovery of the WRAe in Bridge Lake as a cryptotephra further suggests that these cryptotephra deposits may occur more widely at detectable levels in lakes throughout the central NT. The identification of WRAe as a cryptotephra here implies that it may potentially occur throughout the region and thus, once identified, may provide a new isochron for the development of more precise age models and for improved inter- and intra-basinal correlation.
5. The probable presence of WRAe in lake stratigraphic records throughout the region can be used to more precisely delineate the FRE that should be applied to specific lake basins. This application has the potential to improve the resolution of age models calculated for sediment cores within individual lakes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.palaeo.2017.03.031.

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