Holocene tephras in lake cores from northern British Columbia, Canada

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Abstract: Sediment cores recovered from alpine and subalpine lakes up to 250 km apart in northern British Columbia contain five previously unrecognized tephras. Two black phonolitic tephras, each 5–10 mm thick, occur within 2–4 cm of each other in basal sediments from seven lakes in the Finlay River – Dease Lake area. The upper and lower Finlay tephras are slightly older than 10 220 – 10 560 cal year B.P. and likely originate from two closely spaced eruptions of one or two large volcanoes in the northern Cordilleran volcanic province. The Finlay tephras occur at the transition between deglacial sediments and organic-rich postglacial mud in the lake cores and, therefore, closely delimit the termination of the Fraser Glaciation in northern British Columbia. Sediments in Bob Quinn Lake, which lies on the east edge of the northern Coast Mountains, contain two black tephras that differ in age and composition from the Finlay tephras. The lower Bob Quinn tephra is 3–4 mm thick, basaltic in composition, and is derived from an eruption in the Iskut River volcanic field about 9400 cal years ago. The upper Bob Quinn tephra is 12 mm thick, trachytic in composition, and probably 7000–8000 cal years old. A fifth tephra occurs as a cryptotephra near the top of two cores from the Finlay River area and is correlated to the east lobe of the White River tephra (ca. 1150 cal year B.P.). Although present throughout southern Yukon, the White River tephra has not previously been documented this far south in British Columbia. The tephras are valuable new isochrons for future paleoenvironmental studies in northern British Columbia.

Résumé : Des carottes de sédiments prélevées dans des lacs alpins et subalpins, éloignés les uns des autres par des distances atteignant 250 km, et situés dans le nord de la Colombie-Britannique, contiennent cinq tephras antérieurement non identifiés. Deux tephras phonolitiques noirs, chacun d'une épaisseur de 5–10 mm, se trouvent de 2 à 4 cm l'un de l'autre dans les sédiments de base de sept lacs dans le secteur de la rivière Finlay – lac Dease. Les tephras Finlay inférieur et supérieur datent d'un peu avant 10 220 – 10 560 années calendaires avant le présent (années cal. BP) et proviennent probablement de deux éruptions rapprochées d'un ou de deux grands volcans dans le nord de la province volcanique de la Cordillère. Dans les carottes prélevées dans les lacs, les tephras Finlay se trouvent à la transition entre les sédiments de déglaciation et la boue post-glaciaire, riche en matières organiques; ils délimitent donc de manière assez précise la fin de la glaciation Fraser dans le nord de la Colombie-Britannique. Les sédiments dans le lac Bob Quinn, situé à la limite est de la chaîne Côtière septentrionale, contiennent deux tephras dont l'âge et la composition diffèrent des tephras Finlay. Le tephra Bob Quinn inférieur, d'une épaisseur de 3–4 mm, possède une composition basaltique et il provient d'une éruption du champ volcanique de la rivière Iskut survenue il y a environ 9400 années cal. BP. Le tephra Bob Quinn supérieur, d'une épaisseur de 12 mm, a une composition trachytique et il est âgé d'environ 7000–8000 années cal. BP. Un cinquième tephra se retrouve sous forme de cryptotephra près du sommet des deux carottes prélevées dans le secteur de la rivière Finlay; il est corrélé au lobe est du tephra White River (∼1150 années cal. BP). Bien qu'il soit présent dans tout le sud du Yukon, le tephra White River n'a pas été documenté auparavant aussi loin dans le sud de la Colombie-Britannique. Les tephras servent de nouveaux isochrones utiles pour de futures études paléoenvironnementales dans le nord de la Colombie-Britannique.

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Introduction

The northern Cordilleran volcanic province consists of over 100 late Cenozoic volcanic centres in northwest British Columbia, southwest Yukon, and southeast Alaska (Edwards and Russell 1999, 2000). The dominant volcanic rocks in the province are alkali olivine basalt and hawaiite, but highly alkaline rocks such as nephelinite, basanite, peralkaline phonolite, trachyte, and comendite are locally common (Edwards and Russell 2000). Volcanic centres range from small cinder cones to large shield volcanoes and have a broad range of eruptive styles. Cinder cones consisting of basalt and hawaiite are most abundant (Edwards and Russell 2000). Large volcanic complexes, including Hoodoo Mountain, Mount Edziza, Level Mountain, and Heart Peaks, are shield and composite volcanoes with numerous cinder cones (Fig. 1). They are, by far, the largest volcanoes in the northern Cordilleran volcanic province and show the greatest range in petrology (Edwards and Russell 2000).

Several postglacial (i.e., younger than 10 000 ^{14}C year B.P.) lava flows have been identified and mapped in northwest British Columbia (Read et al. 1989; Souther 1992; Villeneuve et al. 1998; Edwards et al. 1999, 2000, 2002; Russell and Hauksdóttir 2000). Distal tephras related to this volcanic activity have not been reported, even though some of the Holocene eruptions were large in volume, and thick tephras have been found near several volcanoes and cinder cones (Read et al. 1989; Souther 1992; Villeneuve et al. 1998; Edwards et al. 1999, 2000, 2002; Russell and Hauksdóttir 2000).

This paper documents four previously unrecognized Holocene tephras in northern British Columbia and the most southern known occurrence of the east lobe of White River tephra (Lerbekmo and Campbell 1969; Lerbekmo et al. 1975; Clague et al. 1995; Froese and Jensen 2005). Two early Holocene phonolitic tephras, named the upper and lower Finlay tephras, occur in sediment cores recovered from lakes up to 250 km apart in the Finlay River – Dease Lake area (Fig. 1). Lake sediment cores from Bob Quinn Lake contain two other Holocene tephras, named the upper and lower Bob Quinn tephras, which are trachytic and basaltic in composition, respectively. Sediment cores from two lakes in the Finlay River area also contain the White River tephra. The objectives of this paper are to (1) describe the geomorphic and stratigraphic settings of the tephras, (2) document their age and distribution, (3) characterize the morphology and the major element composition of their glass shards, and (4) discuss their importance for future paleoenvironmental studies in the region.

Methods

We collected 18 sediment cores from 12 lakes in three areas of northern British Columbia using a percussion coring system (Reasoner 1993). The cores were recovered from lake ice in January 2005 and February 2006 and from the floats of a De Havilland DHC-2 Beaver in July 2005. We cored Red Barrel, Cushing, Katharine, Deep, Black, Bronlund, Rock Fall, and Sandwich lakes in the Finlay River area; of which, Red Barrel, Cushing, Katharine, Deep, and Black lakes contained tephras (Fig. 1; Table 1). We cored Little Glacier, Hungry, and Sister lakes in the Dease Lake area and found tephras in all but Sister Lake (Fig. 1; Table 1). Bob Quinn Lake, at the east edge of the northern Coast Mountains, was also cored, and it too contained tephras (Fig. 1; Table 1). All lake names, except Bob Quinn Lake, are informal.

We transported the sediment cores to the University of Northern British Columbia, Prince George, B.C., where we split, logged, photographed, and analyzed them for bulk physical properties (organic matter, magnetic susceptibility, and grain size). Lithologic and magnetic susceptibility logs for selected cores are presented in Fig. 2. The complete dataset is discussed in Lakeman (2006).

We extracted terrestrial plant macrofossils from the cores for radiocarbon dating. The macrofossils were washed in deionized water, air-dried, and stored in glass vials. Radiocarbon ages were determined by accelerator mass spectrometry at IsoTrace Laboratory (University of Toronto) and Beta Analytic Inc. We calibrated the ages with the program OxCal v4.0, using the IntCal04 calibration curve (Reimer et al. 2004). All calibrated ages are reported at the 95% confidence interval ($\pm 2\sigma$).

We removed glass shards from tephras using a heavy liquid separation procedure and determined the mineralogy of phenocrysts in the glass shards by thin section analysis. We determined the major element composition of these shards, as well as shards from previously identified Holocene scoria from Mount Edziza and shards from a reference sample of the east lobe of White River tephra (UA1043, University of Alberta), using a JEOL 8900 electron microprobe in the Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta. Analyses were performed with the microprobe operating at 15 keV accelerating voltage, a 10 μm beam diameter, and a 6 ηA beam current. All data were normalized to 100% on a water-free basis. A secondary standard of Old Crow tephra (UT1434, University of Toronto; Preece et al. 1999, 2000), a well characterized, secondarily hydrated rhyolite, and a rhyolitic obsidian (UA5831) were analyzed repeatedly together with the samples reported in this study. We report average values for Old Crow tephra from several runs associated with the analyses in this paper in Table 2.

Geomorphic and stratigraphic settings

The sediment cores from the Finlay River – Dease Lake area came from lakes dammed by moraines built during a regional advance of alpine glaciers in northern British Columbia at the end of the Pleistocene (Lakeman et al. 2008). Two tephras are present in the sediments of five of these lakes and are referred to as the upper and lower Finlay tephras (Fig. 1; Table 1). Although most cores contain both tephras, some have only the upper Finlay tephra (Fig. 1; Table 1). The two tephras occur in organic-rich mud, 1–5 cm above its boundary with underlying inorganic silt, sand, and gravel (Fig. 2). The contact between the two units records the transition from deglacial to postglacial sedimentation and the termination of latest Pleistocene valley glaciation in northern British Columbia (Lakeman et al. 2008). The tephras are black, range in thickness from <5 to 10 mm, occur within 2–4 cm of each other in the cores, and are sharply

Fig. 1. (A) Location of volcanic centres and complexes forming the northern Cordilleran volcanic province. Modified from Edwards and Russell (2000). (B) Locations of large volcanic centres, sampled lakes, and occurrences of the Finlay, Bob Quinn, and White River (east lobe) tephras.

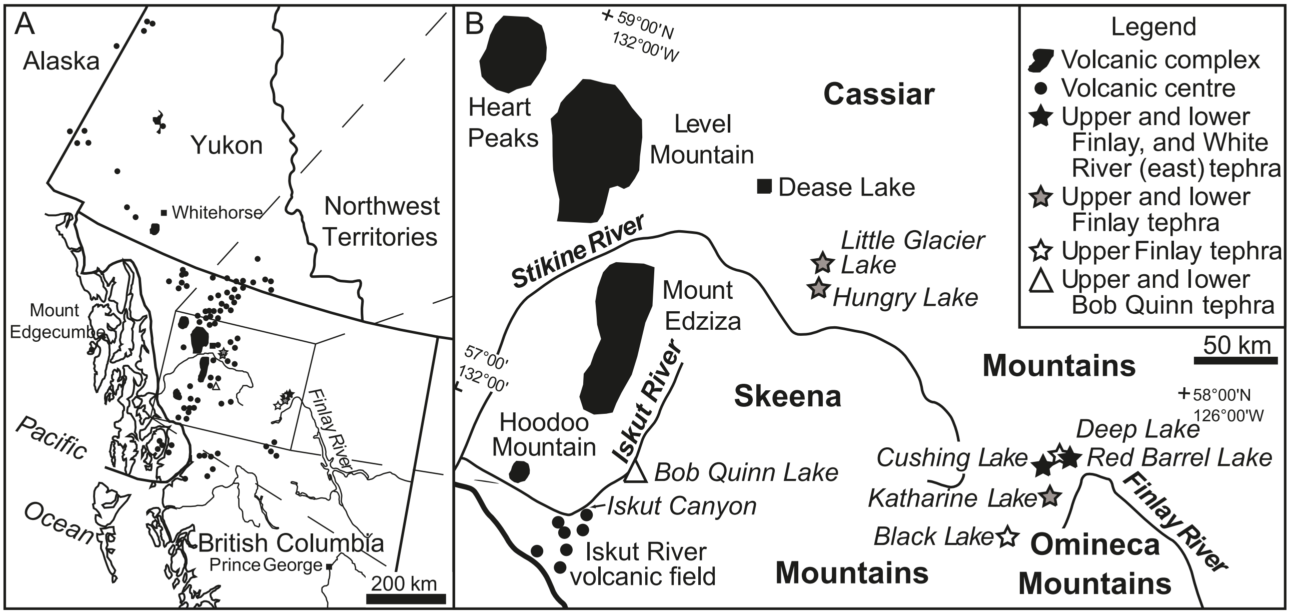


Table 1. Lakes and tephras reported in this study.

Name of lake	Location	Tephra	Laboratory number[a]	Depth in core (cm)	Thickness (mm)	Comments
Black	57°13.686′N, 127°03.115′W	Upper Finlay	—	173.5	10	Undeformed
Bob Quinn	56°58.573′N, 130°15.623′W	Upper Bob Quinn	UA1162	167.5	12	Undeformed
		Lower Bob Quinn	UA1163	206.5	3–4	Undeformed
Cushing	57°35.607′N, 126°54.450′W	White River (east lobe; core 1)	UA1176	10.5–14.5	~40	Dispersed over 4 cm thick horizon
		White River (east lobe; core 2)	UA1256	8.0–15.0	~70	Dispersed over 7 cm thick horizon
		Upper Finlay (core 1)	UA1169	80.0	3–4	Undeformed
		Lower Finlay (core 1)	UA1168	82.5	6–12	Deformed during coring (i.e., coning)
Deep	57°40.943′N, 126°46.372′W	Upper Finlay	—	93.5	15	Undeformed
Hungry	58°04.317′N, 129°19.033′W	Upper Finlay (core 2)	UA1166	90–96	~60	Deformed during coring (i.e., coning)
		Upper Finlay (core 1)	UA1167	36.5–37.5	10–11	Undeformed
Katharine	57°26.643′N, 126°48.582′W	Upper Finlay	UA1171	141–143	1–2	Undeformed
		Lower Finlay	UA1170	148.5	3–6	Undeformed
Little Glacier	58°13.243′N, 129°20.759′W	Upper Finlay	UA1164	75.5	6–10	Deformed during coring (i.e., coning)
		Lower Finlay	UA1165	77.5	6–15	Deformed during coring (i.e., coning)
Red Barrel	57°40.623′N, 126°44.029′W	White River (east lobe)	UA1175	24.5–26.5	~20	Dispersed over 2 cm thick horizon
		Upper Finlay	UA1143	141.5	2–4	Undeformed
		Lower Finlay	UA1144	143.5	3–6	Undeformed

[a]UA, University of Alberta.

bounded by overlying and underlying sediment (Figs. 2, 3A).

A rhyolitic cryptotephra occurs near the top of the Red Barrel and Cushing lake cores (Table 1). It is not visible to the eye, but glass shards are abundant within a 2–7 cm thick zone of organic-rich mud centred at 25.5 cm in the Red Barrel Lake core and 12.0–12.5 cm in two Cushing Lake cores (Fig. 2).

Sediment cores from Bob Quinn Lake contain two tephras that are different from the tephras found in the Finlay River – Dease Lake cores (Fig. 1; Table 1). The lower Bob

Table 2. Average major element composition of glass shards from the tephras found in this study, the reference sample of White River

	Lower Finlay								Upper Finlay			
	UA1144		UA1165		UA1168		UA1170		UA1143		UA1164	
SiO_2	63.27	(2.57)	60.26	(1.73)	60.21	(1.05)	60.25	(1.96)	59.98	(0.71)	59.96	(0.48)
TiO_2	0.33	(0.30)	0.29	(0.20)	0.38	(0.21)	0.56	(0.30)	0.24	(0.06)	0.21	(0.04)
Al_2O_3	18.73	(1.09)	17.13	(1.15)	17.13	(1.10)	18.25	(1.03)	16.53	(0.44)	16.49	(0.38)
FeO(t)	3.31	(2.60)	6.84	(2.09)	6.98	(1.54)	5.78	(2.03)	8.07	(0.30)	7.87	(0.42)
MnO	0.10	(0.08)	0.18	(0.06)	0.18	(0.05)	0.14	(0.06)	0.21	(0.03)	0.21	(0.04)
MgO	0.28	(0.29)	0.15	(0.26)	0.23	(0.28)	0.50	(0.35)	0.03	(0.03)	0.04	(0.05)
CaO	1.43	(0.77)	1.31	(0.52)	1.56	(0.48)	2.02	(0.76)	1.25	(0.08)	1.26	(0.12)
Na_2O	7.07	(0.91)	8.65	(0.83)	8.17	(1.04)	7.38	(1.01)	8.74	(0.79)	9.02	(0.46)
K_2O	5.39	(0.93	4.98	(0.49)	4.97	(0.47)	4.97	(0.48)	4.69	(0.16)	4.71	(0.20)
Cl	0.09	(0.08)	0.20	(0.07)	0.18	(0.08)	0.14	(0.07)	0.26	(0.05)	0.23	(0.04)
H_2O(d)	0.79	(2.06)	0.79	(1.17)	0.75	(1.54)	1.05	(1.35)	0.80	(1.04)	0.92	(1.13)
n	52		71		57		37		41		70	

	Lower Bob Quinn		Upper Bob Quinn		White River (east lobe)					
	UA1163		UA1162		UA1175		UA1176		UA1256	
SiO_2	48.29	(0.49)	59.49	(1.23)	75.10	(1.04)	75.07	(0.75)	75.69	(0.32)
TiO_2	2.40	(0.12)	0.77	(0.25)	0.17	(0.05)	0.21	(0.08)	0.15	(0.05)
Al_2O_3	17.04	(0.22)	18.39	(0.36)	14.05	(0.41)	13.92	(0.48)	13.66	(0.29)
FeO(t)	12.05	(0.31)	6.12	(0.72)	1.29	(0.20)	1.30	(0.22)	1.07	(0.05)
MnO	0.17	(0.03)	0.14	(0.03)	0.03	(0.02)	0.05	(0.02)	0.04	(0.02)
MgO	5.95	(0.27)	0.69	(0.26)	0.26	(0.09)	0.27	(0.08)	0.21	(0.04)
CaO	9.28	(0.12)	2.54	(0.69)	1.59	(0.22)	1.55	(0.19)	1.41	(0.07)
Na_2O	3.84	(0.13)	6.92	(0.28)	3.82	(0.58)	3.88	(0.03)	3.96	(0.13)
K_2O	0.95	(0.05)	4.83	(0.45)	3.37	(0.20)	3.44	(0.23)	3.50	(0.13)
Cl	0.03	(0.02)	0.12	(0.03)	0.32	(0.06)	0.33	(0.07)	0.31	(0.03)
H_2O(d)	1.32	(1.25)	0.42	(1.14)	2.34	(0.65)	2.72	(0.42)	2.45	(0.47)
n	50		53		9		2		5	

Note: All analyses normalized to 100% on a water-free basis, except values for the Old Crow standard (UT1434); standard deviation in parentheses. University of Alberta; UT, University of Toronto.

Quinn tephra is 3–4 mm thick and is about 5 cm above the contact between organic-rich mud and underlying inorganic silt (Figs. 2, 3B). A second tephra, which is 12 mm thick, is 40 cm above the lower tephra, within organic-rich mud (Figs. 2, 3B).

Composition and age

The two Finlay tephras have fine sand to coarse silt textures. Their glass shards are similar in morphology: most are blocky and have spherical vesicles (Fig. 3A). Needle-shaped shards with lineated, lensoid vesicles are also present but are less common (Fig. 3A). Phenocrysts in glass shards of both tephras are dominantly plagioclase with subordinate orthopyroxene. Both tephras are phonolitic to trachytic in composition and rich in FeO (Figs. 4, 5; Table 2). The two tephras have similar major element composition, indicating that they are likely derived from the same source. However, unlike the upper Finlay tephra, the chemical composition of the lower Finlay tephra is bimodal (Fig. 5). One population of the lower Finlay shards has 58–67 wt.% SiO_2; CaO and MgO decrease as SiO_2 increases; TiO_2 increases as FeO increases; and it has more Al_2O_3 than the other population (Fig. 5). The second population of lower Finlay shards has 59–62 wt.% SiO_2; generally lower values of CaO, MgO, and Al_2O_3; and plots within the upper Finlay tephra chemical field (Fig. 5).

Terrestrial plant macrofossils 2–2.5 cm above the upper Finlay tephra yielded ages of 9780 – 10 250 cal year B.P. (8960 ± 80 ^{14}C year B.P.) and 10 220 – 10 560 cal year B.P. (9180 ± 80 ^{14}C year B.P.) (Fig. 2; Table 3). The two tephras are thus early Holocene in age and were probably deposited immediately after deglaciation (Clague 1981).

The lower Bob Quinn tephra has a medium-coarse sand texture. Glass shards are blocky and needle-shaped, up to 5 mm in length, and contain plagioclase, clinopyroxene, and minor orthopyroxene phenocrysts (Fig. 3B). Most of the blocky shards contain spherical vesicles, whereas the needle-shaped shards have lineated, lensoid vesicles (Fig. 3B). The lower tephra is trachybasaltic with approximately 12 wt.% FeO (Figs. 4, 6; Table 2). The upper Bob Quinn tephra has a silty fine sand texture. Glass shards are dominantly blocky and have spherical vesicles (Fig. 3B). Phenocrysts in glass shards are primarily plagioclase; pyroxene and potassium feldspar crystals are uncommon. The tephra is trachytic and closely resembles the first population of the lower Finlay tephra dataset, indicating they may be from the same source (Figs. 4, 5). Terrestrial plant macrofossils directly above and below the lower Bob Quinn tephra yielded ages of 9320–9540 cal year B.P. (8450 ± 50 ^{14}C year B.P.) and 9270–9500 cal year B.P. (8370 ± 40 ^{14}C year B.P.), respectively (Fig. 2; Table 3). The calibrated age ranges overlap and indicate that the tephra was deposited about 9400 cal year B.P.

tephra (east lobe), and the secondary standard of Old Crow tephra.

				Upper Finlay (?)			
UA1169		UA1171		UA1166		UA1167	
59.88	(0.72)	60.28	(0.45)	59.98	(0.36)	60.14	(0.25)
0.24	(0.07)	0.23	(0.03)	0.22	(0.05)	0.21	(0.04)
16.24	(0.47)	16.53	(0.44)	16.21	(0.14)	16.23	(0.17)
8.21	(0.31)	7.67	(0.29)	8.07	(0.26)	8.03	(0.21)
0.22	(0.04)	0.21	(0.05)	0.20	(0.04)	0.20	(0.04)
0.02	(0.02)	0.03	(0.02)	0.03	(0.02)	0.03	(0.02)
1.28	(0.09)	1.22	(0.07)	1.22	(0.09)	1.23	(0.05)
8.95	(0.47)	8.87	(0.35)	9.11	(0.24)	8.93	(0.20)
4.72	(0.10)	4.72	(0.23)	4.72	(0.09)	4.74	(0.11)
0.24	(0.05)	0.24	(0.03)	0.24	(0.02)	0.25	(0.04)
0.98	(1.05)	1.04	(1.66)	1.34	(0.89)	1.59	(0.85)
59		8		18		20	

White River (east lobe) reference		Old Crow standard	
UA1043		UT1434	
75.30	(0.58)	71.66	(1.21)
0.14	(0.05)	0.28	(0.04)
13.92	(0.25)	12.42	(0.24)
1.15	(0.13)	1.63	(0.07)
0.04	(0.03)	0.06	(0.03)
0.22	(0.08)	0.28	(0.04)
1.45	(0.09)	1.39	(0.05)
3.96	(0.14)	3.45	(0.19)
3.51	(0.15)	3.44	(0.11)
0.33	(0.04)	0.26	(0.03)
3.24	(1.20)	5.16	(1.63)
19		81	

FeO(t), total iron oxide as FeO; H_2O(d), water by difference; *n*, number of analyses; UA,

The upper Bob Quinn tephra has not been dated, but assuming a constant sedimentation rate for the upper 207 cm of the core, it was deposited about 7000–8000 cal year B.P. (Fig. 2).

The uppermost tephra in the Red Barrel and Cushing lake cores is rhyolitic and chemically identical to a reference sample of the east lobe of White River tephra (UA1043, Table 2), which is about 1150 cal year old (Clague et al. 1995).

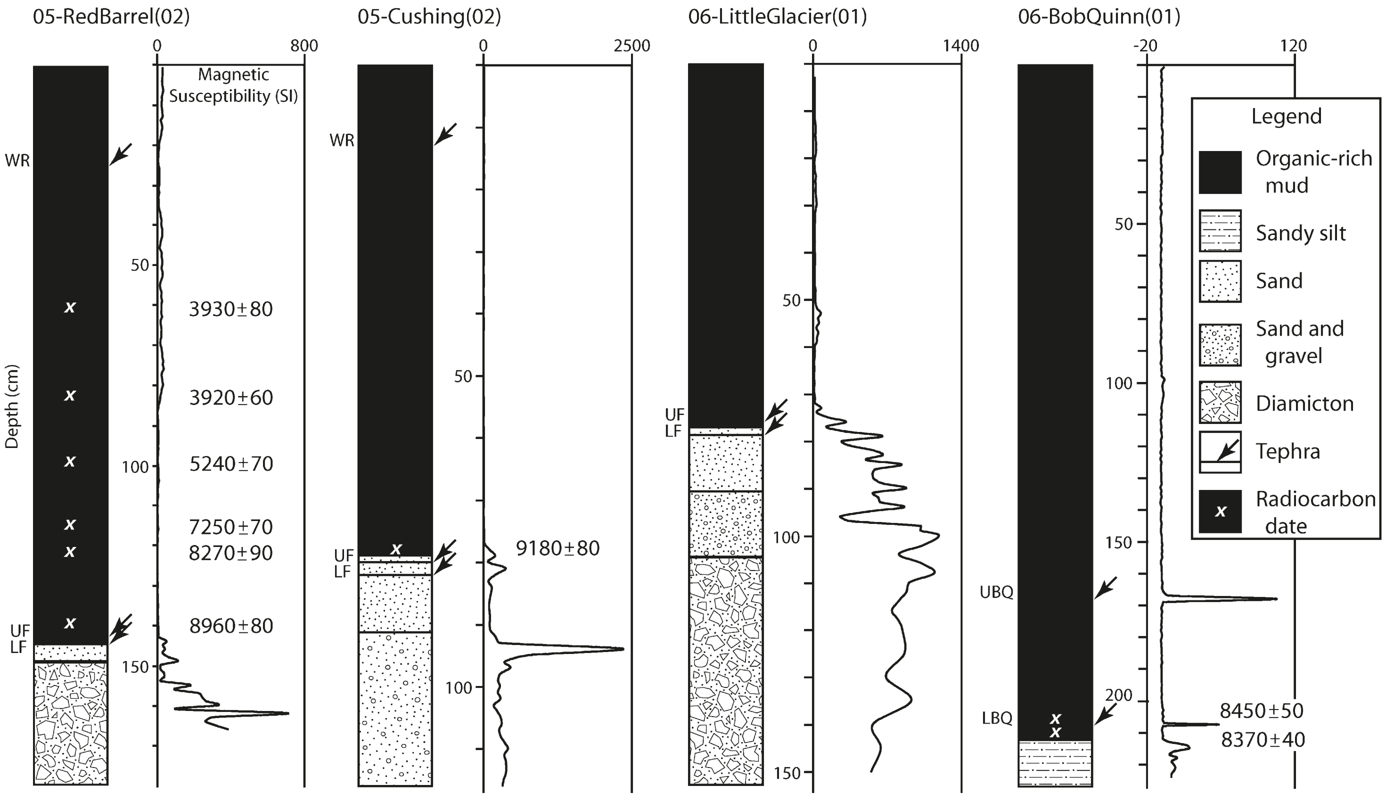
Sources and distribution of the early Holocene tephras

Based on their distributions, thicknesses, and compositions, the four early Holocene tephras have sources in the northern Cordilleran volcanic province (Fig. 1). Highly alkaline rocks with compositions similar to the phonolitic and trachytic tephras of this study are characteristic of this volcanic province (Fig. 4; Edwards and Russell 1999, 2000). Tephras sourced from volcanoes in the Wrangell volcanic field and the Aleutian Arc are dominantly rhyolitic to dacitic in composition, indicating that those regions are unlikely source areas (Lerbekmo and Campbell 1969; Lerbekmo et al. 1975; Preece et al. 1992, 1999, 2000; Richter et al. 1995; Westgate et al. 2000; Mangan et al. 2003; Froese and Jensen 2005). Late Pleistocene tephras from Mount Edgecumbe, southeastern Alaska (Fig. 1), range in composition from basaltic to rhyolitic, but all except one are local in extent (Heusser 1960; McKenzie 1970; Yehle 1974; Riehle et al. 1992). The only Edgecumbe tephra of regional extent is dacitic in composition and approximately 13 050 – 13 260 cal year old (11 250 ± 50 ^{14}C year old) (Riehle et al. 1992; Begét and Motyka 1998), older than the tephras identified in this study and erupted at a time when most of northern British Columbia was still covered by glacier ice (Clague 1981). Nevertheless, possible, unidentified volcanic centres in southeast Alaska and northwest British Columbia that are presently below sea level or covered by glaciers cannot be ruled out as possible sources for the Finlay and Bob Quinn tephras.

Finlay tephras

The two Finlay tephras are distributed across northwest British Columbia and possibly extend into the northern Rocky Mountains. Based on their distribution, thickness, and major element composition, the source is one of the large shield or composite volcanoes in northwest British Columbia, probably Hoodoo Mountain, Mount Edziza, Level Mountain, or Heart Peaks (Fig. 1). Some cinder cones in the northern Cordilleran volcanic province erupted following deglaciation during the late Pleistocene or early Holocene, but they are too small to account for the thickness and distribution of the Finlay tephras.

Fig. 2. Stratigraphic and magnetic susceptibility logs and radiocarbon ages for cores collected from Red Barrel, Cushing, Little Glacier, and Bob Quinn lakes. UF, upper Finlay tephra; LF, lower Finlay tephra; UBQ, upper Bob Quinn tephra; LBQ, lower Bob Quinn tephra; WR, White River tephra (east lobe; occurs as a cryptotephra).



The major element compositions of the Finlay tephras are most similar to those of whole-rock samples from Hoodoo Mountain (Fig. 4; Tables 2, 4), a large composite volcano with a long history of phonolitic and trachytic eruptive activity dating from 85 000 to ~9000 year ago (Edwards 1997; Edwards et al. 2002). Two phonolitic lava flows on the south flank of Hoodoo Mountain are postglacial in age, based on an absence of modification by glacier ice and ^{40}Ar–^{39}Ar dates of 9000 – 10 000 year B.P. (Villeneuve et al. 1998; Edwards et al. 1999, 2002). The average whole-rock chemistry of the two postglacial phonolitic flows is similar to the glass composition of the Finlay tephras (Fig. 4; Tables 2, 4), but no pyroclastic flows or tephra fall deposits are known from the eruptions that produced these lava flows (Edwards et al. 2002). The core from Bob Quinn Lake, which is only 60 km northeast of Hoodoo Mountain and lies along the trajectory that any ash plume would take moving from that volcano to the Finlay River and Dease Lake areas (Fig. 1), does not contain the Finlay tephras. The basal sediments of that core, however, are about 1000 years younger than the Finlay tephras. The compositional data indicate that Hoodoo Mountain is the most likely source for the Finlay tephras, but other possible sources cannot be ruled out.

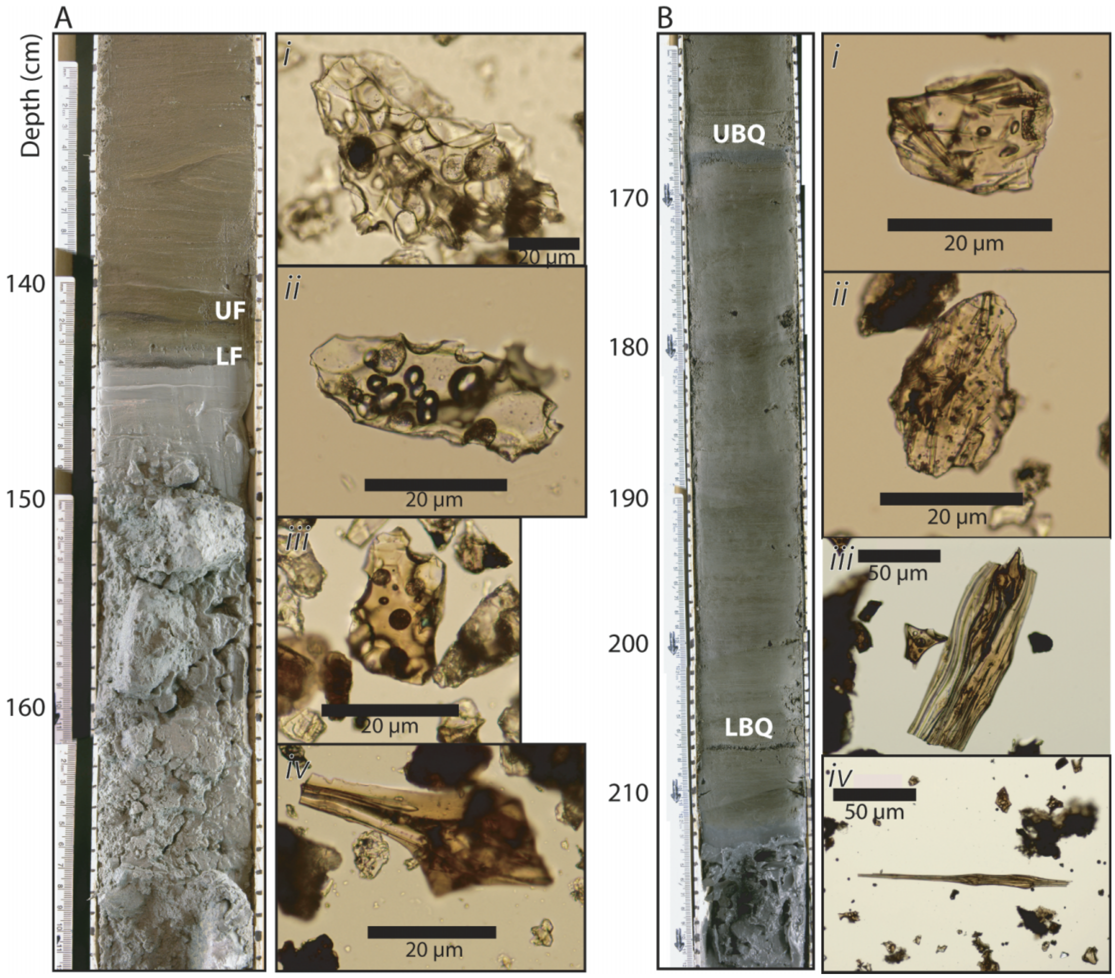
Mount Edziza is another large volcanic complex in the northern Cordilleran volcanic province and a possible source of the Finlay tephras. It is a broad plateau consisting of multiple, large, ice-covered composite cones and numerous small cinder cones (Fig. 1; Souther 1992). The volcanic complex has a diverse suite of rocks ranging in composition from basaltic to peralkaline felsic (Souther 1992). These rocks are generally less alkaline than the Finlay tephras, although some have similar compositions (Fig. 4). Comenditic trachyte pumice of the Sheep Track Member of the Big Raven Formation is postglacial in age and covers an area of about 40 km^2 on the west flank of Mount Edziza (Souther 1992). The pumice, although highly alkaline, shows significantly less variance than both the Finlay tephras and is compositionally distinct (Figs. 4, 5). Older formations of possible late Pleistocene to early Holocene age are dominantly basaltic and limited in extent (Souther 1992). However, their absolute ages and chemical compositions are poorly known, consequently, Mount Edziza cannot be ruled out as a possible source for the Finlay tephras.

Level Mountain and Heart Peaks are large volcanic complexes similar in size and chemistry to Mount Edziza and Hoodoo Mountain (Figs. 1, 4; Casey 1980; Hamilton 1981, 1991; Souther and Yorath 1991; Edwards and Russell 2000). They have received little scientific study, and it is unknown whether Holocene deposits are present and, if they are, whether they are extensive. Consequently, further field and laboratory investigations are required to assess whether the Finlay tephras originated from Level Mountain or Heart Peaks.

Bob Quinn tephras

The age and composition of the lower Bob Quinn tephra strongly suggest that it is derived from the Iskut River volcanic field. This volcanic field consists of eight centres situ-

Fig. 3. (A) Sediments from Red Barrel Lake showing the upper (UF) and lower (LF) Finlay tephras and typical glass shards ((*i*) and (*ii*) of UF and (*iii*) and (*iv*) of LF). Shards are dominantly blocky with spherical vesicles, but needle-shaped shards with lineated, lensoid vesicles are also present. (B) Sediments from Bob Quinn Lake showing the upper (UBQ) and lower (LBQ) tephras and typical glass shards ((*i*) and (*ii*) of UBQ and (*iii*) and (*iv*) of LBQ). Shards in the upper tephra are dominantly blocky with spherical vesicles; Shards in the lower tephra are dominantly elongate and needle-shaped with lineated, lensoid vesicles.



ated between Iskut and Unuk rivers, ∼40 km southwest of Bob Quinn Lake (Fig. 1; Table 4). The presence of large, needle-shaped glass shards in the tephra indicates that Bob Quinn Lake is near the source of the eruption. Volcanism in the Iskut River volcanic field ranges in age from ∼70 000 to 150 year B.P. (Russell and Hauksdóttir 2000). Read et al. (1989) demonstrated that two basalt flows sourced from the Iskut River volcanic centre about 4 km east-southeast of Iskut Canyon temporarily dammed Iskut River during the early Holocene (Fig. 1). They reported ages of 8390 – 11 630 cal year B.P. (8730 ± 600 ^{14}C year B.P.) from charcoal underlying one of the basalt flows and 9540 – 10 200 cal year B.P. (8780 ± 150 ^{14}C year B.P.) from plant material bounding basaltic tephra that mantles nearby slopes (Table 3). These ages accord with the 9400 cal year B.P. age assigned to the lower tephra in the Bob Quinn Lake core. The major element composition of whole-rock samples collected from the Iskut River volcanic field overlaps with that of the lower Bob Quinn tephra (Figs. 4, 6; Tables 2, 4).

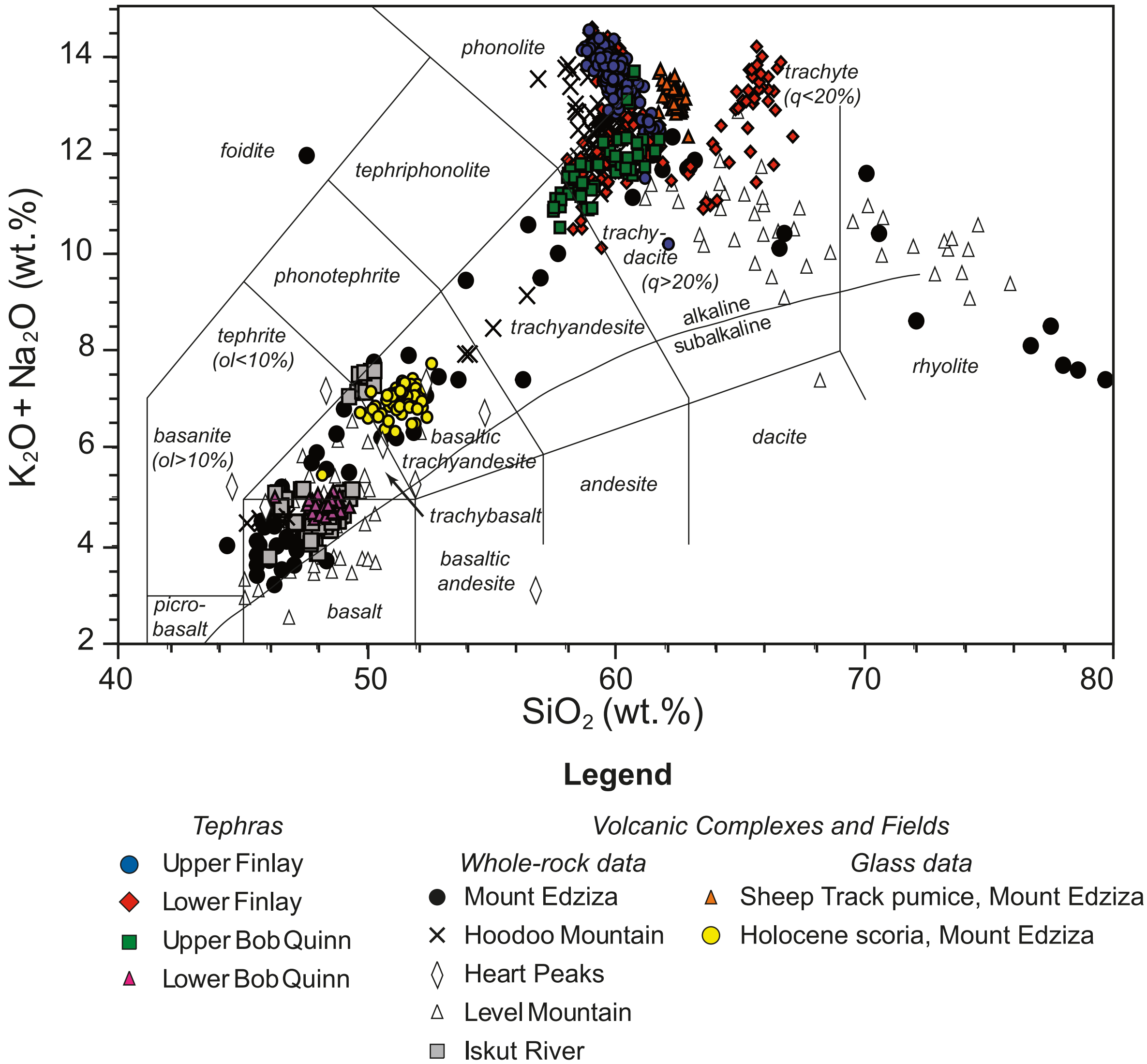
The upper Bob Quinn tephra is similar in composition to the lower Finlay tephra and to whole-rock samples from Hoodoo Mountain and Mount Edziza (Figs. 4, 5; Tables 2, 4). Its composition is closest to that of whole-rock values from the two postglacial phonolitic lava flows on Hoodoo Mountain, but the ages of the flows must be better constrained to confirm this possible correlation.

The spatial distributions of the upper and lower Bob Quinn tephras are poorly constrained. The lower Bob Quinn tephra probably extends along Iskut River, south of Mount Edziza, based on its proposed affinity to the Iskut River volcanic field. However, it may not be present much farther east in northern British Columbia because of its coarse grain size and limited thickness. The upper Bob Quinn tephra may extend farther east than the lower tephra, but it has not yet been found in the Finlay River or Dease Lake areas.

Discussion

The tephras identified in this study are important new isochrons for Holocene paleoenvironmental records in northern British Columbia. The Finlay and White River tephras were deposited at times when significant climatic and environmental changes were occurring in the Northern Hemisphere. The Finlay tephras closely delimit the time of terminal

Fig. 4. Plot of K_2O + Na_2O versus SiO_2 (LeBas et al. 1986) comparing glass-derived, normalized values for the Finlay tephras, Bob Quinn tephras, and Sheep Track pumice and Holocene scoria from Mount Edziza against whole-rock values for several volcanic complexes in northwest British Columbia. (modified from Edwards and Russell (2000)). ol, olivine; *q*, quartz.



Pleistocene deglaciation in northern British Columbia (Clague 1981) and mark the onset of early Holocene organic sedimentation in alpine lakes. They also help to correlate late-glacial moraines that record a regional advance of alpine glaciers across northern British Columbia (Lakeman et al. 2008). The late-glacial moraines suggest that alpine glaciers advanced in response to a regional climatic deterioration at the end of the last glaciation, possibly during the Younger Dryas chronozone (11 500 – 12 800 cal year B.P.; Alley 2000). The Finlay tephras could also be used to better constrain the extent of glaciers in northern British Columbia in the early Holocene, especially in areas closer to their source where the tephras would be thicker and better preserved.

Eruption of the east lobe of the White River tephra coincides with a marked change in sedimentation in Red Barrel and Cushing lakes, which are located within glacierized catchments (Fig. 7). At 24 and 9 cm depth in the Red Barrel and Cushing lake cores, respectively, the amount of organic matter decreases and magnetic susceptibility increases. These changes signify a shift to higher clastic sedimentation in the lakes, perhaps owing to glacier expansion at the beginning of the Little Ice Age ~1150 cal year B.P. The occurrence of the east lobe of White River tephra in north-central British Columbia extends its known range ~200 km south of the southern limit reported by Robinson (2001) and Froese and Jensen (2005), suggesting an aerial distribution in excess of 540 000 km^2 (Froese and Jensen 2005).

The cause of the bimodal distribution in the compositional data derived from the lower Finlay tephra is unknown. Gehrels et al. (2006) demonstrated that a sample of Taupo tephra from a peat section in New Zealand contained two populations of glass shards, one with the characteristic major element chemistry of Taupo tephra and a second with an exotic chemical composition. They speculated that the exotic population originated from mixing of an older tephra, multiple phases in a single eruption, or two simultaneous eruptions from different vents (see also Shane et al. 2008

Fig. 5. Compositions of glass from the Finlay tephras, upper Bob Quinn tephra, and Sheep Track pumice plotted on oxide variation diagrams (normalized values).

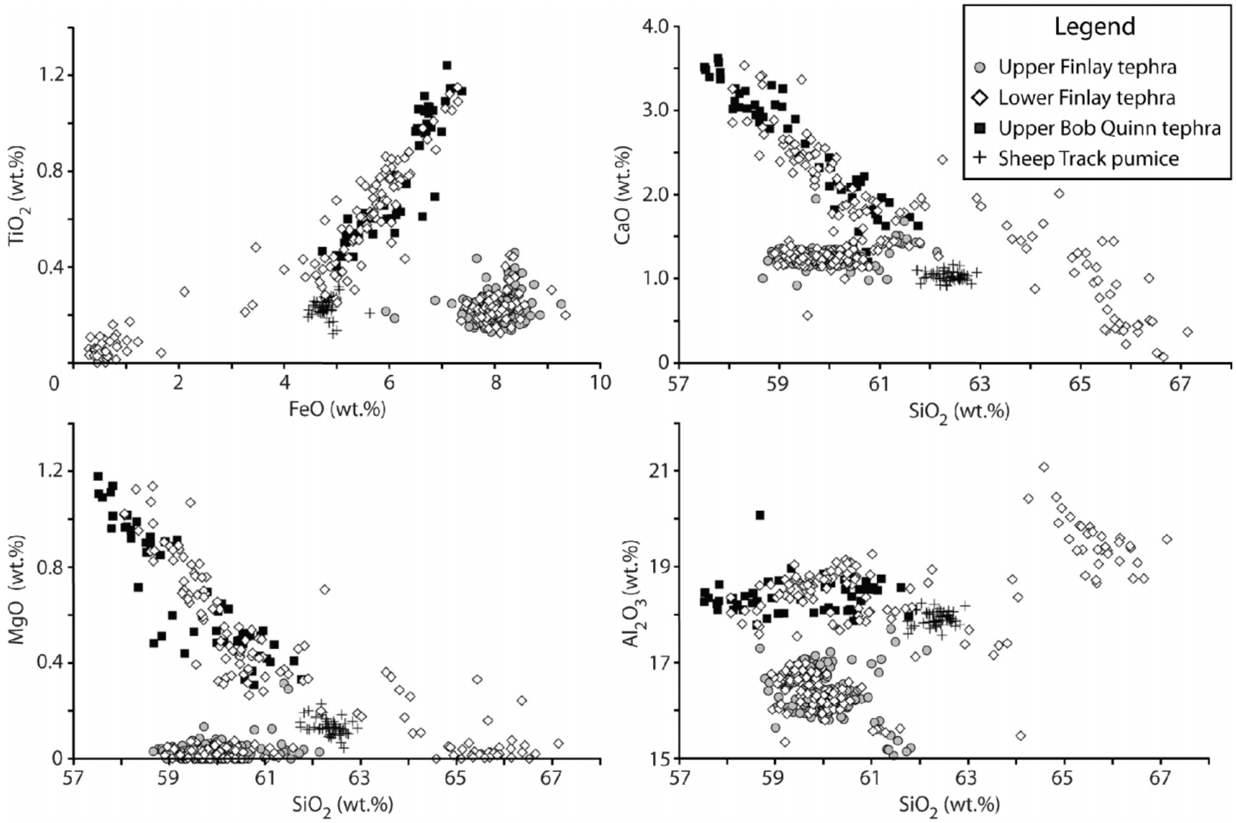


Fig. 6. Compositions of glass from the lower Bob Quinn tephra and Holocene scoria from Mount Edziza and of rocks from the Iskut River volcanic field plotted on oxide variation diagrams (normalized values). Iskut River data from Russell and Hauksdóttir (2000).

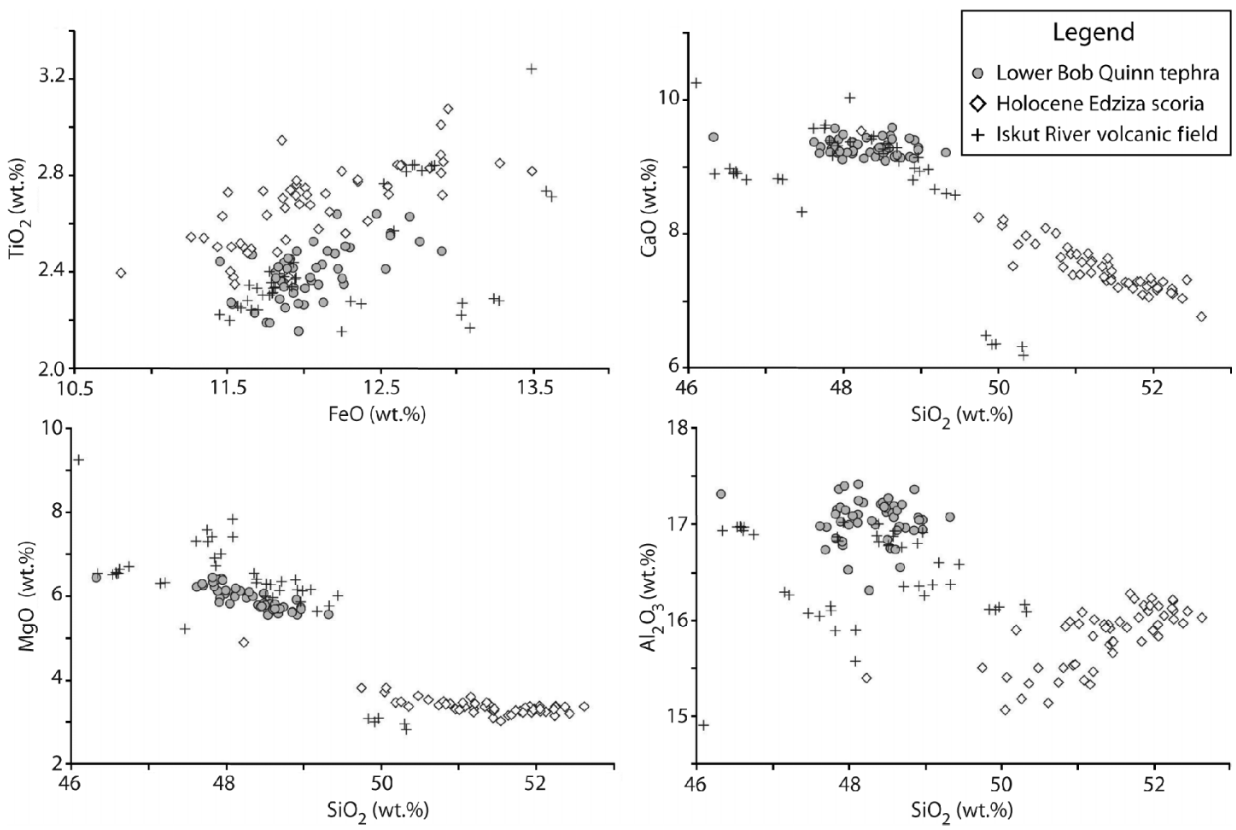


Table 3. Radiocarbon ages reported in this paper.

Location (latitude, longitude)	^{14}C age (years B.P.)[a]	Calibrated age range (years B.P.)[b]	Laboratory number[c]	Dated material	Depth in core (cm)	Reference
Red Barrel Lake (57°40.623′N, 126°44.029′W)	3930±80	4100–4580	TO-12469	Conifer needle	60.5	This study
	3920±60	4160–4520	TO-12470	Twig	82.5	This study
	5240±70	5890–6210	TO-12471	Spruce terminal bud	98.5	This study
	7250±70	7950–8190	TO-12472	Twig	115.0	This study
	8270±90	9030–9460	TO-12473	Conifer needle	121.5	This study
	8960±80	9780–10250	TO-12474	Wood	139.5	This study
Crushing Lake (57°35.607′N, 126°54.450′W)	9180±80	10220–10560	TO-12475	Terrestrial plant matter	77.5	This study
Bob Quinn Lake (56°58.573′N, 130°15.623′W)	8450±50	9320–9540	Beta-216498	Wood	206.5	This study
	8370±50	9270–9500	Beta-216499	Terrestrial plant matter	207.5	This study
Iskut River (56°41.448′N, 130°36.748′W)	8730±600	8390–11630	?	Charcoal	—	Read et al. (1989)
	8750±150	9540–10200	SFU-???	?	—	Read et al. (1989)

[a]Laboratory-reported errors are 1σ.
[b]Calibrated ages determined using the program OxCal v4.0 Beta, which uses the IntCal04 calibration curve (Reimer et al. 2004). The range represents the 95% confidence interval ($\pm 2\sigma$).
[c]Beta, Beta Analytic Inc., Miami, Florida; SFU, Simon Fraser University; TO, IsoTrace Laboratory (University of Toronto).

for other examples of compositional heterogeneities in New Zealand tephras). Similar explanations are possible in the case of the lower Finlay tephra.

Another possible explanation for the bimodal chemical composition is that the lower Finlay tephra has been contaminated by downward, density-induced migration of the upper one through the sediment column shortly after deposition, a process suggested for other tephras by Anderson et al. (1984), White and Osborn (1992), and Beierle and Bond (2002). Downward migration of the upper Finlay tephra is plausible if one or two samples exhibited the bimodal distribution. However, the bimodal distribution is common to all samples of the lower tephra collected from five lakes up to 250 km apart. Furthermore, the Finlay tephras are sharply bounded by 2–4 cm of silt and sand that would seemingly preclude density-induced, downward migration of tephra. We conclude that more sample sites and compositional data are needed to explain the bimodal distribution in the lower Finlay tephra dataset. In addition, more research is required into the eruptive histories and magmatic evolution of the large volcanoes of the Northern Cordilleran volcanic province. Of particular importance, is the identification of proximal tephra deposits from suspected source vents, which would enable comparison of the Finlay and Bob Quinn tephras with glass-derived compositional data instead of the whole-rock values reported here (e.g., Fig. 4).

Conclusions

Four, previously unrecognized tephras are reported from northern British Columbia. Their distribution and major element composition indicate sources at one or more volcanic centres in the northern Cordilleran volcanic province. Two phonolitic tephras in the Finlay River – Dease Lake area, named the upper and lower Finlay tephras, are products of two closely spaced eruptions shortly before 10 220 – 10 560 cal year B.P. The Finlay tephras are regional deposits and occur at the transition from deglacial sediments to organic-rich Holocene mud in alpine lakes. They closely delimit the time of terminal Pleistocene deglaciation in northern British Columbia. Cores from Bob Quinn Lake also contain two tephras, named the upper and lower Bob Quinn tephras, which differ in age and composition from the Finlay tephras. The lower basaltic tephra at Bob Quinn Lake is about 9400 cal years old and has a source at the Iskut River volcanic centre. The upper trachytic tephra at Bob Quinn Lake is ~7000–8000 cal years old; its source is unknown. A fifth tephra that is geochemically identical to the east lobe of White River tephra is present in two lakes in the Finlay River area as a cryptotephra. These occurrences extend the southern limit of the White River tephra by ~200 km. Collectively, the tephras represent valuable isochrons for future paleoenvironmental studies in northern British Columbia.

Acknowledgements

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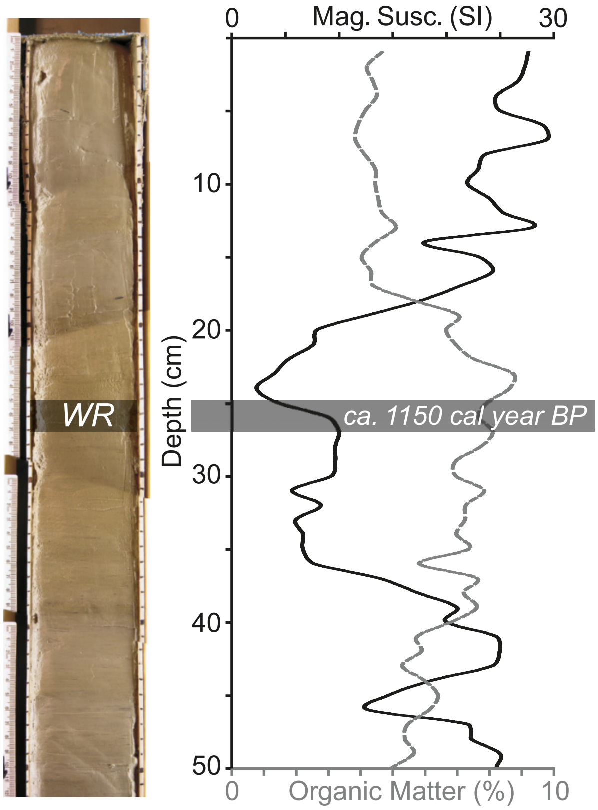
Table 4. Average whole-rock major element composition of postglacial phonolitic flows at Hoodoo Mountain and Holocene basalt flows derived from several volcanic centres in the Iskut River volcanic field. Average major element composition of glass from Holocene scoria from Mount Edziza is also shown.

	Hoodoo Mountain		Iskut River volcanic centres															
			Iskut River		Tom MacKay Creek		Snippaker Creek		Cone Glacier		Cinder Mountain		King Creek		Second Canyon		Lava Fork	
SiO_2	60.12	n/a	48.53	(0.55)	48.08	n/a	48.36	(0.43)	48.24	(0.69)	49.63	(1.08)	49.44	n/a	46.10	n/a	46.57	(0.12)
TiO_2	0.29	n/a	2.30	(0.07)	2.30	n/a	2.30	(0.03)	2.37	(0.17)	2.41	(0.41)	2.24	n/a	2.57	n/a	2.83	(0.03)
Al_2O_3	16.81	n/a	16.61	(0.30)	15.57	n/a	16.65	(0.35)	16.47	(0.41)	16.11	(0.03)	16.58	n/a	14.90	n/a	16.95	(0.03)
Fe_2O_3	4.59	n/a	2.97	(0.68)	3.26	n/a	3.32	(1.35)	4.48	(1.77)	3.95	(0.81)	2.77	n/a	4.30	n/a	3.53	(1.01)
FeO	3.26	n/a	8.76	(0.62)	8.51	n/a	8.53	(1.06)	7.65	(1.45)	9.25	(0.78)	8.52	n/a	8.29	n/a	9.19	(0.94)
MnO	0.19	n/a	0.18	(0.01)	0.18	n/a	0.18	(0.00)	0.19	(0.01)	0.25	(0.02)	0.18	n/a	0.18	n/a	0.18	(0.00)
MgO	0.21	n/a	6.48	(0.36)	7.83	n/a	6.48	(0.47)	6.50	(0.70)	3.36	(0.92)	6.01	n/a	9.26	n/a	6.58	(0.07)
CaO	1.68	n/a	9.07	(0.19)	10.03	n/a	9.37	(0.15)	9.18	(0.35)	6.67	(0.82)	8.58	n/a	10.25	n/a	8.90	(0.05)
Na_2O	7.74	n/a	3.63	(0.16)	2.90	n/a	3.48	(0.08)	3.51	(0.19)	4.55	(0.34)	3.76	n/a	2.85	n/a	3.73	(0.15)
K_2O	5.03	n/a	1.04	(0.14)	0.94	n/a	0.94	(0.06)	1.00	(0.14)	2.43	(0.60)	1.38	n/a	0.91	n/a	1.09	(0.01)
P_2O_5	0.06	n/a	0.43	(0.05)	0.38	n/a	0.39	(0.02)	0.42	(0.04)	1.39	(0.28)	0.54	n/a	0.39	n/a	0.45	(0.00)
H_2O(d)	1.22	n/a	0.30	(0.05)	0.70	n/a	0.18	(0.08)	0.26	(0.12)	0.76	(0.65)	0.53	n/a	0.62	n/a	0.18	(0.06)
n	n/a		8		1		5		13		6		1		1		7	

	Mount Edziza											
	Sheep Track pumice						Williams cone		Englacial cinders		Cinders on tundra	
	UA1155		UA1156		UA1157		UA1149		UA1150		UA1153	
SiO_2	62.37	(0.31)	62.35	(0.24)	62.34	(0.27)	52.09	(0.29)	50.54	(0.76)	51.47	(0.39)
TiO_2	0.23	(0.04)	0.23	(0.04)	0.24	(0.03)	2.49	(0.10)	2.85	(0.09)	2.69	(0.08)
Al_2O_3	18.00	(0.13)	17.87	(0.15)	17.88	(0.13)	16.06	(0.10)	15.45	(0.21)	15.97	(0.16)
FeO(t)	4.83	(0.24)	4.76	(0.12)	4.77	(0.15)	11.55	(0.31)	12.72	(0.40)	12.00	(0.21)
MnO	0.12	(0.03)	0.13	(0.04)	0.12	(0.03)	0.17	(0.04)	0.21	(0.04)	0.18	(0.05)
MgO	0.13	(0.03)	0.14	(0.04)	0.13	(0.04)	3.29	(0.08)	3.55	(0.38)	3.31	(0.12)
CaO	1.05	(0.05)	1.01	(0.06)	1.02	(0.06)	7.17	(0.16)	7.88	(0.50)	7.38	(0.18)
Na_2O	7.92	(0.21)	7.92	(0.20)	7.92	(0.18)	4.62	(0.26)	4.58	(0.22)	4.63	(0.24)
K_2O	5.15	(0.14)	5.34	(0.13)	5.36	(0.10)	2.50	(0.10)	2.18	(0.23)	2.33	(0.08)
Cl	0.21	(0.03)	0.25	(0.10)	0.21	(0.03)	0.04	(0.03)	0.05	(0.02)	0.05	(0.02)
H_2O(d)	–0.05	(0.91)	0.98	(0.43)	1.30	(1.04)	0.80	(0.38)	1.28	(0.67)	1.09	(0.67)
n	20		12		19		16		18		19	

Note: Data from Hoodoo Mountain reprinted with permission from Edwards et al. (2002). Data from the Iskut River volcanic field reprinted with permission from Russell and Hauksdóttir (2000). All analyses are normalized to 100% on a water-free basis. Standard deviation in parentheses. FeO(t), total iron oxide as FeO; H_2O(d), water by difference; *n*, number of analyses.

Fig. 7. Sediment lithologies, organic matter, and magnetic susceptibility for the top 50 cm of the Red Barrel Lake sediment core. The stratigraphic position of the east lobe of White River (WR) tephra is indicated, which approximates the onset of Little Ice Age sedimentation in the lake basin. Mag. Susc., magnetic susceptibility.



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