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OVER 16,000 YEARS OF FIRE FREQUENCY DETERMINED FROM AMS RADIOCARBON DATING OF SOIL CHARCOAL IN AN ALLUVIAL FAN AT BEAR FLAT, NORTHEASTERN BRITISH COLUMBIA

A J Timothy Jull

University of Arizona, NSF Arizona AMS Laboratory, P.O. Box 210081, Tucson, Arizona 85721, USA.
Email: jull@email.arizona.edu.

Marten Geertsema

British Columbia Forest Service, 1011 4th Avenue, Prince George, British Columbia, Canada V2L 3H9.
Email: marten.geertsema@gov.bc.ca.

ABSTRACT. We present results of radiocarbon dating of charcoal from paleosols and buried charcoal horizons in a unique sequence, which potentially records the last 36,000 yr, from a fan at Bear Flat, British Columbia (BC) (56°16′51″N, 121°13′39″W). Evidence for forest-fire charcoal is found over the last 13,500 ± 110 ^{14}C yr before present (BP) or 16,250 ± 700 cal BP. The study area is located east of the Rocky Mountains in an area that was ice-free at least 13,970 ± 170 ^{14}C yr BP (17,450–16,150 cal BP) ago. The latest evidence of fire is during the Medieval Warm Period (MWP). The charcoal ages show a periodicity in large fires on a millennial scale through the Holocene—an average of 4 fires per thousand years. Higher fire frequencies are observed between 2200 to 2800 cal BP, ~5500 and ~6000 cal BP, ~7500 to 8200 cal BP, and 9000 to 10,000 cal BP. These intervals also appear to be times of above-average aggradation of the fan. We conclude that fire frequency is related to large-scale climatic events on a millennial time scale.

INTRODUCTION

The long-term record of forest-fire history has been studied in a number of regions (Meyer et al. 1995, 2001; Cwynar 1987; Long et al. 1998; Hallett et al. 2003a,b; Millspaugh et al. 2000; Horn and Sanford 1992; Turcq et al. 1998; Lertzman et al. 2002; Hallett and Walker 2000; Pierce et al. 2004) of the world, but there is little information on fire history in more northerly regions of Canada. There are basically 2 kinds of studies: 1) direct measurement of charcoal found in alluvial and colluvial deposits (e.g. Meyer et al. 1995, 2001; Lertzman et al. 2002; Pierce et al. 2004); and 2) studies of the charcoal record found in lake sediments (e.g. Long et al. 1998; Millspaugh et al. 2000). In southern British Columbia (BC), there have been several studies (Hallett et al. 2003a,b; Lertzman et al. 2002) of fire histories in hemlock rainforests of the Fraser Valley, southwestern BC. Hallet and Walker (2000) studied fire from charcoal recovered from a lake in Kootenay National Park (southeastern BC), and Gavin (2003a) has studied fires in west-coast temperate rain forests on Vancouver Island. Sanborn et al. (2006) have studied fires from soil charcoal in an interior rain forest in east-central BC.

The purpose of this paper is to provide preliminary results of charcoal radiocarbon dates obtained from a fan in the Peace River area of northeastern BC and to begin establishing a prehistoric fire history for the area. Refinement of these results is forthcoming as charcoal dates from other fans in the area will be added to the database. Results of this study also have implications for local glacial refugia, but this topic is beyond the scope of this paper and will be dealt with in a subsequent publication.

SETTING

Our study site is located on a fan on a fluvial terrace of the Peace River (see Figure 1), at a location (Figure 2) known as Bear Flat (56°16′51″N, 121°13′39″W). The site is located in a drier portion of the Peace variant of the Black and White Boreal Spruce biogeoclimatic zone (DeLong 1998; Meidinger and Pojar 1991) and is influenced by southern exposure in the Peace River valley. The slopes are often covered with aspen (*Populus tremuloides*) forest or grassland steppe. The Bear Flat site has been farmed since at least 1949—the time of the earliest aerial photographs. An aerial photograph of the area is given in Figure 1. The site was selected because it exposed an excellent record of paleosols and because there are no published results on long-term forest-fire history this far north in BC.

Figure 1 Oblique aerial photograph of the alluvial fan at Bear Flat, BC

In addition, the region is close to the area of coalescence of the Cordilleran and Laurentide ice sheets (Catto et al. 1996) and was covered by Glacial Lake Peace at the end of the Pleistocene. A date on wood charcoal on Lake Peace sediments overlying the Laurentide ice sheet till in the Fort St. John region gave an age of 13,970 ± 170 ^{14}C yr BP (Catto et al. 1996), equivalent to a calibrated age

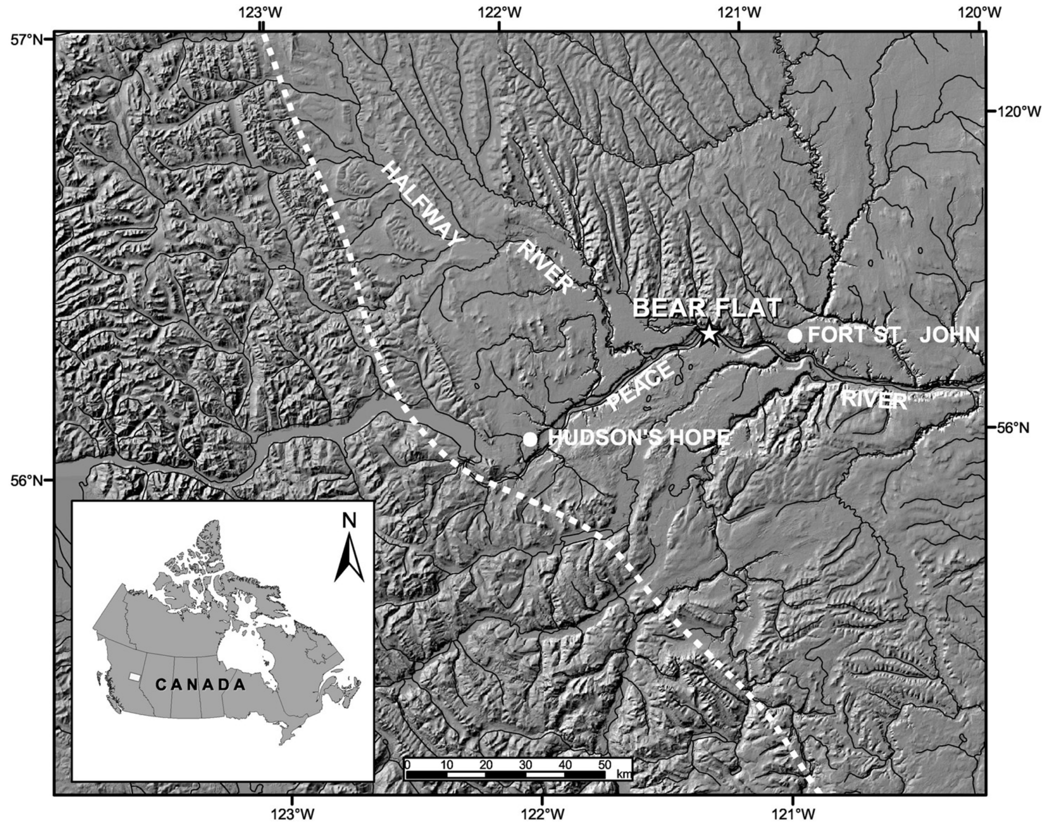

Figure 2 Location of Bear Flat adjacent to the Peace River, northern BC. Note the location of the maximum western extent of the Laurentide ice sheet (dotted line), estimated by Catto et al. (1996) from the distribution of Laurentide erratics. These authors also reported a ^{14}C date on wood charcoal, from the contact of Laurentide till and overlying Glacial Lake Peace sediments in the Fort St. John region, of 13,970 ± 170 ^{14}C yr BP (15,500–14,200 cal BP).

range of 17,450–16,150 cal BP. Also, dates on terrestrial plants confirm that this area was ice-free by ~12,500 ^{14}C yr BP; in calibrated years, this corresponds to an age range of 15,600–14,200 cal BP, as reported by Dyke et al. (2001).

Contributing Catchment Area

The fan at Bear Flat (Figure 3) has been mapped as a colluvial clay fan of the Taylor soil association (Lord and Green 1986). The fan has a gentle gradient with a mid to distal slope of 6%, indicating gentle low-energy deposition, ideal for the preservation of buried horizons. The fan is similar to the arid fans described by Bull (1964) and is responsive to flash flood deposition. The fan contains numerous charcoal-rich horizons (see Figure 4). In our model, charcoal accumulated in 2 ways: 1) as detritus entrained in alluvial and colluvial sediment flows from the adjacent hillslopes subsequent to fire (and during other erosion events); and 2) from material burned in situ. While wind deposition of charcoal is also possible, the fan sediments were not as such identified as eolian materials. The size of the charcoal delivering catchment varied with time. During the Wisconsin glaciation, prior to the development of Glacial Lake Peace (Matthews 1980), isolated refugia may have existed perhaps with rare fires or with preserved wood burning at much later dates. The locations of these refugia are unknown

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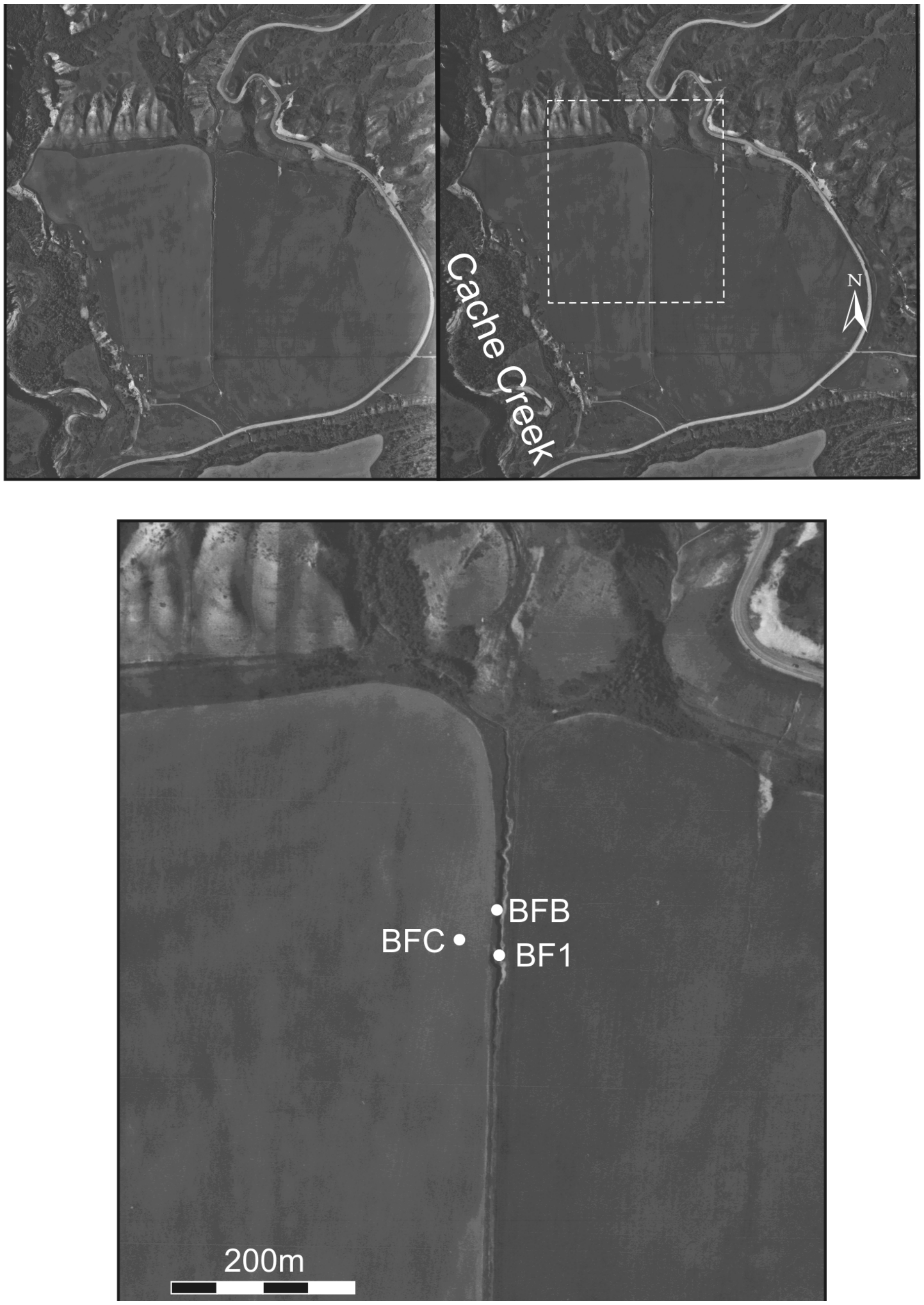

Figure 3 a) Stereo image of the Bear Flat site. b) Detailed view of the Bear Flat fan showing the specific locations of the 3 cores: BF1, BFB, and BFC.

to us, but presumably occurred near the zone of coalescence of the Laurentide and Cordilleran ice sheets. Indeed, these may have been shifting refugia. Later, as Glacial Lake Peace emerged and went through various stages of growth, charcoal from refugia and from contemporaneous fires in the local

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contributing watershed may have been collected in and redistributed through the ice-dammed lake. This charcoal is stored in the sediments of Glacial Lake Peace and redistributed by landslides and erosive transport. After the ice dam broke and Glacial Lake Peace drained, the Peace River incised itself through the lake sediments, constructing several tiers of terraces. The fan at Bear Flat is constructed on one of these terraces. Transport of charcoal from fires postdating the construction of the fan comes from a much smaller local catchment area. Charcoal predating the fan could have arrived from a much larger area and thus has an uncertain provenance. We recognize that it may not be possible to rule out eolian transport of some fine-grained material, as Valentine et al. (1980) described a section further to the east along the Peace River with eolian deposits in a clifftop dune. Nonetheless, the ages are important as they represent times of at least isolated unglaciated conditions.

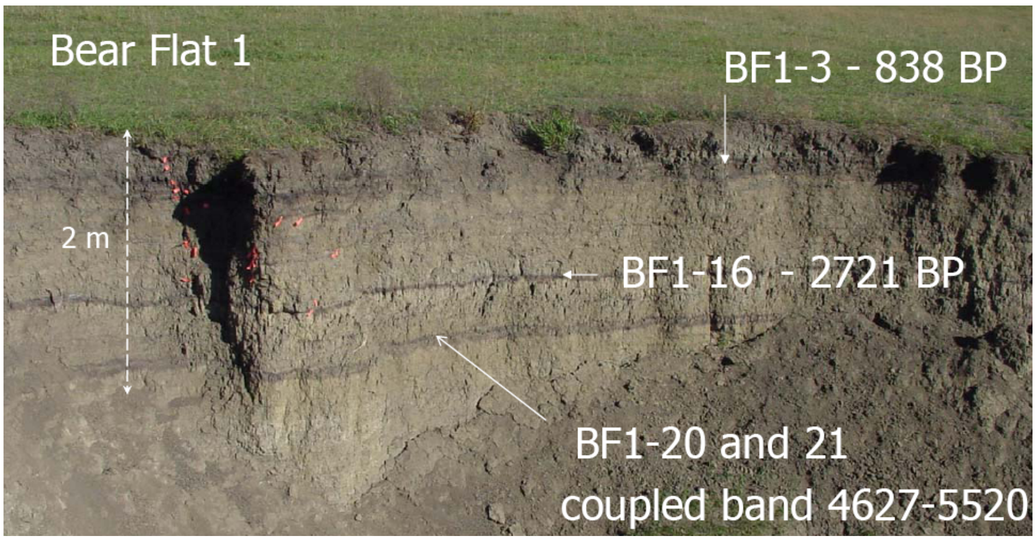

Figure 4 View of the exposure of the buried fire horizons at the Bear Flat 1 location. Discrete charcoal horizons are marked with the red tags, and major fire events are clearly visible in this photograph.

METHODS

We sampled charcoal and charcoal-rich sediments from paleosols, some of which are fire-reddened at a gully incised into the fan (Figure 4). The sampling locations (see Figure 2b) occurred in the mid to distal portion of the fan at 2 exposures and from 1 drilled core. The core was extracted using Shelby tubes and the split spoon method. As noted in Table 1, many samples contained macroscopic charcoal, and other horizons were found to contain apparently macroscopic charcoal, which fell apart during pretreatment to give a mixture of sediment and finely divided material. Where possible, we treated charcoal fragments samples using the conventional acid-alkali-acid cleaning procedure (Bird, forthcoming). Charcoal fragments were picked from the cleaned material and combusted in the presence of CuO to CO_2. The gas was then reduced to graphite for accelerator mass spectrometry (AMS) dating. In some cases, macroscopic charcoal was not present after pretreatment, as some samples were mostly fine clay-rich mineral sediment, or the charcoal fragments disintegrated after pretreatment. In these cases, it was not possible to separate finely dispersed charcoal (<0.1 mm) from these materials. These samples were pretreated with the acid-base-acid treatment, washed, dried, and then combusted at 400 °C in oxygen (McGeehin et al. 2001), which should only sample the organic carbon.

Table 1 List of ^{14}C dates (* indicates a duplicate).

Code (AA-)	Sample	Target #	Depth (cm)	Pretr.	Material	Combustion temp (°C)/agent	$\delta^{13}C$ (–)	mg C recovered	C (%)	^{14}C age used in plot	^{14}C age (BP)	Mean
39484	BF-1-1	J472A	17.5	ABA	charcoal	900 CuO	26.3	0.506	6.30	913	877 ± 35	913 ± 44
44985	BF-1R1	J632A		ABA	charcoal	900 CuO	26.8	2.84	47.90		966 ± 42	
41172	BF-1-2	J532A	25	ABA	charcoal	900 CuO	25.3	0.638	18.80	838	838 ± 39	
39485	BF-1-3	J473A	36	ABA	charcoal	900 CuO	26.3	1.89	45.10	1245	1245 ± 28	
41173	BF-1-4	J533A	39.5	ABA	charcoal, 3 pc	900 CuO	27.3	0.6	75.00	1489	1489 ± 40	
41174	BF-1-5[a]	J534A	44.5	ABA	charcoal	900 CuO	26.6	1.124	48.90	1950	1950 ± 40	
		J534RA		ABA	charcoal	900 CuO	26.6	0.851	50.00	1770	1770 ± 58	
41175	BF-1-6	J535A	49.5	ABA	charcoal	900 CuO	26.5	0.835	49.10	1961	1961 ± 40	
39486	BF-1-7	J474A	51.5	ABA	charcoal	900 CuO	28	0.415	7.40	2146	2222 ± 47	2146 ± 79
44986	BF-1-7R1	J633		ABA	charcoal	900 CuO	28.3	1.37	50.70		2063 ± 49	
41176	BF-1-8	J536B	57.5	ABA	charcoal	900 CuO	24.3	1.6	64.00	2133	2133 ± 40	
41177	BF-1-9	J537A	68	ABA	charcoal, 3 pc	900 CuO	25.2	2.08	41.50	2258	2258 ± 38 2225 ± 61*	
39487	BF-1-10[b]	J475A	79	ABA	charcoal	900 CuO	26.3	1.099	2.50		3891 ± 41	
		J475LA				400 O_2	26.6	1.174	19.60	2367	2349 ± 59	2367 ± 41
		J475HA				800 O_2	25.3	1.058	17.60		2384 ± 56	
41178	BF-1-11	J538A	85	ABA	char-rich sed	900 CuO	26.1	0.132	4.90	3217	3620 ± 110	
44987	BF-1-11R1	J634LA		ABA	char/sed	400 O_2	27.4	1.16	1.94		3217 ± 51	3288 ± 154
41179	BF-1-12	J539A	88	ABA	char frg + sed	900 CuO	24.4	0.213	17.80	2447	2447 ± 63	
39488	BF-1-13	J476A	99	ABA	charcoal	900 CuO	26.2	2.12	54.30	2471	2471 ± 41	
41180	BF-1-14	J540LA	110	ABA	char/sed	400 O_2	31.9	1.043	1.60	3182	3182 ± 70	
		J540HA				800 O_2	26.6	0.278	0.43		4460 ± 130	
44988	BF-1-14R1	J635		ABA	charcoal	900 CuO	(25)	0.75	1.90		4634 ± 35	
41181	BF-1-15	J541A	118	ABA	charcoal, 2 pc	900 CuO	23.1	0.633	27.50	2573	2573 ± 55	
39489	BF-1-16	J477A	126.5	ABA	charcoal	900 CuO	25.6	4.92	39.10	2721	2721 ± 37	
41182	BF-1-17[c]	J542LA	146	ABA	SED	400 O_2	26.2	2.699	0.85		7996 ± 56	
		J542HA	146	ABA	sed	800 O_2	25.3	0.47	0.15		9336 ± 56	
		J542A	146	ABA	charcoal	900 CuO	25.3	0.091	1.50	6370	6370 ± 110	
		J542RLA	146	ABA	char/sed	400 O_2	29.3	1.23	1.40		11,080 ± 100	
41183	BF-1-18[d]	J543LA	157	ABA	sed	400 O_2	25.00	1.79	1.56	5297	4688 ± 48	
		J543HA		ABA	sed	800 O_2	25.00	2.03	1.76		5496 ± 48	
		J543RLA	157	ABA	sed	400 O_2	26.90	1.70	1.30		5468 ± 54 5542 ± 40*	5297 ± 157
		J543RHa		ABA	sed	800 O_2	26.90	1.72	1.10		6217 ± 49	
		J543LR3	157	ABA	sed/char	400 O_2	27.50	1.23	1.40		5763 ± 93	
44989	BF-1-18R1	J636LA		ABA	char/sed	400 O_2	27.10	1.50	1.93		5594 ± 59	

Table 1 List of ^{14}C dates (* indicates a duplicate). *(Continued)*

Code (AA-)	Sample	Target #	Depth (cm)	Pretr.	Material	Combustion temp (°C)/agent	$\delta^{13}C$ (–)	mg C recovered	C (%)	^{14}C age used in plot	^{14}C age (BP)	Mean
41184	BF-1-19	J544LA	170	ABA	sed	400 O_2	29.40	0.08	1.10		5280 ± 180	
		J544RLA	170	ABA	sed	400 O_2 rpt	27.60	1.24	3.10	5137	5137 ± 57	
44990	BF-1-19R1	J637LA		ABA	char/sed	400 O_2	27.20	0.60	0.81		13,330 ± 120	
39490	BF-1-20	J478A	180.5	ABA	charcoal	900 CuO	24	2.78	38.70	4627	4627 ± 45	
41185	BF-1-21	J545A	189	ABA	charcoal, picked	900 CuO	23	0.07	14.20	5520	5520 ± 150	5747 ± 100
		J545LA		ABA	char/sed	400 O_2	25.7	1.77	0.11		5791 ± 66	
		J545HA		ABA	char/sed	800 O_2	23	2.405	0.15		6539 ± 52	
44991	BF-1-21R1[c]	J638LA		ABA	char/sed	400 O_2	29.7	0.076	0.44		13,310 ± 760	
41186	BF-1-22[c]	J546A	261	ABA	sed	400 O_2	30.1	0.101	0.46		8940 ± 190	
		J546LRA	261	ABA	sed	400 O2	25.9	2.29	0.85	8126	8126 ± 91	
41187	BF-1-23	J547A	263	ABA	charcoal	900 CuO	25.3	0.750	8.60		7880 ± 120	
44993	BF-1-23R1	J640A		ABA	sed	400 O_2	25	1.770	10.70	7861	7849 ± 94	7861 ± 74
39491	BF-1-24	J479A		ABA	charcoal	900 CuO	25.1	0.147	48.90	6410	6410 ± 130	
	BF-1-24	J479LRA	272	ABA	charcoal	400 O_2	26.7	1.5	12.00	6373	6373 ± 66	
	BF-1-24[c]	J479LA				400 O_2	25.4	0.84	0.49		15,480 ± 100	
	BF-1-24[c]	J479HA				800 O_2	25.4	1.134	0.66		14,010 ± 340	
41188	BF-1-25	J548A	338	ABA	charcoal	900 CuO	24.5	0.542	41.70	7011	7011 ± 56	
41189	BF-1-26	J549A	341	ABA	charcoal	900 CuO	26	1.078	34.80	6839	6839 ± 52	
41190	BF-1-27	J550LA	350	ABA	sed	400 O_2	26.2	0.167	0.77		9610 ± 150	
		J550RA		ABA	sed	400 O_2	26.2	0.056	1.40	9860	9860 ± 370	
39492	BF-1-28	J480A	363	ABA	charcoal	900 CuO	22.3	0.911	10.10	7126	7126 ± 52	
44996	BF-1-28R1	J643A		ABA	charcoal, choke cherry	400 O_2	25.8	2.25	6.90		8342 ± 72	
41191	BF-1-29	J551LA	386	ABA	sed	400 O_2	27.4	1.35	2.64	10,530	10,530 ± 100 10,479 ± 94*	
	BF-1-29	J551Ma		ABA	sed	400–550 O_2	27.4	0.132	0.26		9230 ± 160	
41192	BF-1-30	J593LA	415	ABA	sed	400 O_2	(25)	1.81	0.57		16,870 ± 110	
44998	BF-1-30R1	J645		ABA	sed	400 O_2	(25)	0.93	8.80	9627	9627 ± 68	
44999	BF-1-30A	J646	420	ABA	sed	400 O_2	(25)	0.5	1.98	13,530	13,530 ± 110	
39493	BF-1-31	J481LA		ABA	charcoal	400 O_2	26.4	1.57	0.73		8255 ± 83	8151 ± 120
	BF-1-31	J481LB									8013 ± 96	
	BF-1-31	J481HA				800 O_2	25.4	1.109	0.52		9106 ± 83 8650 ± 170	9018 ± 180

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Table 1 List of ^{14}C dates (* indicates a duplicate). *(Continued)*

Code (AA-)	Sample	Target #	Depth (cm)	Pretr.	Material	Combustion temp (°C)/agent	$\delta^{13}C$ (–)	mg C recovered	C (%)	^{14}C age used in plot	^{14}C age (BP)	Mean
44236	BFB-1	J609A	385	ABA	charcoal	900 CuO	23.2	1.99	66.50	10,008	10,008 ± 83	
44237	BFB-2	J610A	475	ABA	charcoal, cont. band	900 CuO	26.2	2.18	34.60	6941	6941 ± 55	
44238	BFB-3	J611A	486	ABA	charcoal, paleosol, fire-red	900 CuO	25.8	2.33	41.62	7053	7053 ± 59	
44239	BFB-4	J612A	488	ABA	charcoal, paleosol	900 CuO	22.8	1.91	53.10	7132	7132 ± 80	
44240	BFB-5	J613A	510	ABA	charcoal	900 CuO	27.2	0.2	1.70	8230	8230 ± 110	
44241	BFB6	J614	535	ABA	charcoal	900 CuO	26.1	0.43	0.20		7816 ± 21	
44242	BFB7	J615	540	ABA	charcoal	900 CuO	25.8	0.2	n.a.	7100	7100 ± 130	
44243	BFB8	J616	550	ABA	charcoal	900 CuO	23.5	0.36	n.a.	7235	7235 ± 68	
44244	BFB9	J617	565	ABA	charcoal	900 CuO	26.4	0.29	2.30	8620	8620 ± 140	
44245	BFB10	J618	585	ABA	char/sed	400 O_2	31.5	0.056	0.34		8410 ± 190	
44246	BFB11	J619L	600	ABA	char/sed	400 O_2	27.2	0.25	0.42		10,780 ± 140	
		J619H		ABA	sed	800 O_2	25.5	0.26	0.43		11,350 ± 140	
44247	BFB12[e]		641									
44248	BFB13	J621LA	650	ABA	char/sed	400 O_2	26.9	2.32	5.20	8626	8626 ± 60	
44249	BFB14	J622A	652	ABA	char/sed, fire-red.	400 O_2	28.1	0.3	1.82	9520	9520 ± 140	
44250	BFB15	J623	670	ABA	charcoal	900 CuO	23.3	0.24	5.22	8445	8445 ± 99	
44251	BFB16	J624RL	710	ABA	sed	400 O_2	27.5	0.12	0.42		8290 ± 270	
44252	BFB17	J625LA	730	ABA	char/sed	400 O_2	0.835	0.041	1.00		no result	
44253	BFB18	J626	750	ABA	char/sed	900 CuO	25.8	0.57	0.75		11,170 ± 100	
44254	BFB19	J627L	760	ABA	char/sed	400 O_2	28	0.1	0.19		10,400 ± 1400	
44255	BFB20[f]	J628LA	780	ABA	sed	400 O_2	25.4	0.6	0.49		17,090 ± 260	
		J628HA		ABA	sed	800 O_2	25.3	0.26	0.21		24,810 ± 580	
44256	BFB21	J629LA	790	ABA	sed/org matter	400	25.8	2.13	n.a.		17,830 ± 110	
48081	BFC 646	T16199	646	ABA	sed	900 CuO	25.6	0.42	0.60		15,780 ± 160	
		T16199LA	646	ABA	sed	400 O_2	26.4	1.15	0.50	10,588	10,588 ± 80	
48082	BFC 654	T16200	654	ABA	sed	900 CuO	25.6	0.38	0.60		19,600 ± 250	
		T16200LA	654	ABA	sed	400 O_2	26.2	0.88	0.34	20,540	20,990 ± 173	
48083	BFC666	T16201	666	ABA	sed	900 CuO	25.3	0.53	0.80		20,600 ± 230	
		T16201LA	666	ABA	sed	400 O_2	25.8	1.61	0.60	20,487	20,431 ± 162	20,487 ± 132

Table 1 List of ^{14}C dates (* indicates a duplicate). *(Continued)*

Code (AA-)	Sample	Target #	Depth (cm)	Pretr.	Material	Combustion temp (°C)/agent	$\delta^{13}C$ (–)	mg C recovered	C (%)	^{14}C age used in plot	^{14}C age (BP)	Mean
47059	BFC 9.50	V16158A	950	ABA	sed	400 O_2	25.71	1.37	0.26		17,720 ± 180	
48084	BFC 9.71	T16202R	971	ABA	sed	900 CuO	25.4	0.62	0.70		23,510 ± 240	
		T16202LA	971	ABA	sed	400 O_2	26.6	1.16	0.40	23,965	24,718 ± 309	23,965 ± 585
47060	BFC 10-60	V16159A	1060	ABA	sed	400 O_2	27.3	1.85	0.68		29,400 ± 390	
47061	BFC 10-63	V16160	1063	ABA	sed	400 O_2	(25)	0.36	n.a.		19,870 ± 350	
47062	BFC 10-92	V16161	1092	ABA	sed	400 O_2	25.8	1.17	0.15		20,920 ± 260	
		V16161RA	1092	ABA	sed/char	400 O_2	(25.8)	1.76	1.04	11,340	11,340 ± 75	
47063	BFC 11.13	V16162	1113	ABA	sed	400 O_2	(25)	1.11	0.49		23,920 ± 190	
47064	BFC 15.00	V16163	1500	ABA	sed	400 O_2	24.5	1.58	0.21		16,660 ± 130	
		V16163Ra	1500	ABA	sed	400 O_2		1.82	0.85	16,310	16,310 ± 220	
47065	BFC 15.00a	V16164	1505	ABA	sed	400 O_2	25.7	1.53	0.20		20,370 ± 270	
47066	BFC 16.49-1709	T16203L	1679	ABA	sed	400 O_2	26.15	2.02	0.60	35,892	35,892 ± 781	

[a]Different charcoal fragments.
[b]Reject, prefer lower temperature step.
[c]Reject, <1% C.
[d]Mean of 5 dates.
[e]No CO_2; sample lost, to be repeated.
[f]Reject, <0.5% C.

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RESULTS AND DISCUSSION

It is important to establish the age of the fan to separate the older and larger contributing catchment from the younger and smaller Holocene catchment. To do this, we attempt to distinguish between in situ and detrital charcoal. We distinguish horizons with occasional charcoal fragments from horizons with continuous bands of charcoal, and attribute the former to detrital charcoal (transported either a long or a short distance) and the latter to possible in situ charcoal. Strong evidence for in situ charcoal is an intact subjacent fire-reddened horizon (Dormaar and Lutwick 1975). Ketterings and Bigham (2000) note that soil reddening occurs when the soil has been heated to >600 °C for over 45 min. It is difficult to envision large-scale mass transport of such a horizon without brecciating. In addition, we feel that dating larger macroscopic charcoal is more reliable than smaller fragments, as they can be transported relatively long distances by wind.

The lowest fire-reddened material is encountered at 420 cm depth and yields an age of 16,250 ± 700 cal BP. As the long-distance transport of charcoal with fire-reddened sediment is unlikely, this may represent a minimum age of the fan and thus a minimum age for the drainage of Glacial Lake Peace. The oldest continuous charcoal layer at 386-cm depth yields an age of 10,530 ± 100 ^{14}C yr BP, which gives a calibrated range of 10,780–10,306 BC (1 σ) and 10,845–10,198 BC (2 σ). This age postdates the age range of 15,600–14,200 BP of Dyke et al. (2001) of a minimum age of Glacial Lake Peace. Our study does not solve this deglacial landscape issue, but provides additional data for consideration.

Difference in Ages of Charcoal

We assessed the problem of sampling different-aged charcoals by dating more than 1 sample from the same horizon. Reasonable agreement was obtained, but with differences ranging from 31 to 1280 ^{14}C yr BP. This study of 7 duplicates gave a mean difference of 360 ^{14}C yr and a standard error (1 σ) of 380 yr. One horizon (BF1-17; 146 cm) gave a wide range of ^{14}C ages. In such cases where different results were obtained, it is not clear if material from the same tree was dated, or the charcoal was derived from several fires of different ages, older charcoal was incorporated, or if fine older charcoal was present in the dated sample for some other reason, as discussed by Lertzman et al. (2002). Clearly, such effects limit the accuracy of dating fire recurrence in soils at the century scale.

Dating of Fire and Fire-related Horizons

A complete list of our results for Bear Flat is given in Table 1. In Figure 5, we show results for samples from 50 charcoal horizons that yielded >1% C. We also include results of 6 samples below ~6.5-m depth that yielded 0.3–1.0% C during combustion. These samples contained scattered small pieces of charcoal, and we used the C content as an estimate of the significance of these samples. Some other samples with as little as 0.2% C were measured, but these showed a wide scatter in age and were excluded from Figure 5 on the basis of their very low C yield, since these dates could easily be affected by detrital carbon or eolian transport of older carbon. Amounts of carbon dated range from 0.04 to 2.8 mg. In order to avoid confusion, we will refer to all ages in calibrated years before present (cal BP), although we include ^{14}C ages in Table 1. Calibrated ^{14}C ages were obtained using the IntCal04 calibration (Reimer et al. 2004).

The sediment sequence in the Bear Flat fan contains several large, thick charcoal-rich horizons, some of which are fire-reddened (see Figure 4), as well as less distinct layers without fire-reddening that also contain charcoal. The most recent fires, observed in this record, occurred during the Medieval Warm Period (MWP), with 2 charcoal-rich horizons dated at 913 ± 44 and 838 ± 39 ^{14}C yr BP, corresponding to 2-σ confidence limits of 930–730 cal BP and 910–670 cal BP, respectively; how-

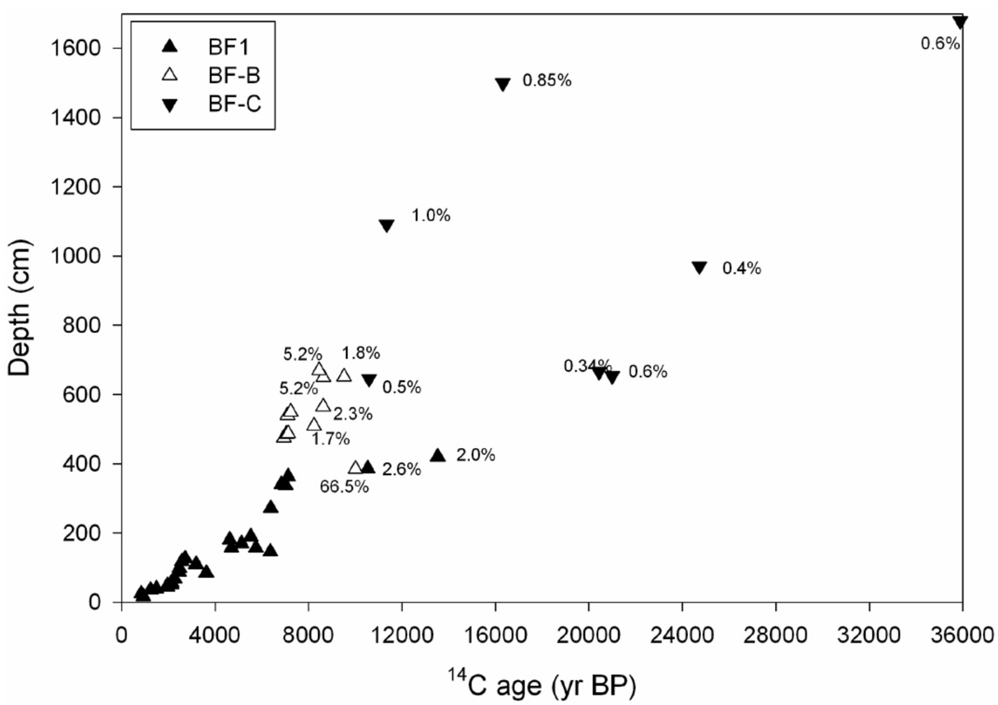

Figure 5 Plot of ^{14}C ages of the charcoal-rich soil horizons versus depth. Note the divergence of the plot beyond 8000 ^{14}C yr BP. The carbon yields on combustion of some of the older samples are shown, including the 6 samples yielding <1% C. Samples where no yield is indicated all gave much larger yields of carbon on combustion.

ever, in the second case, 85% of the probability is between 800–670 cal BP. Obviously, there may have been very localized fires that are not seen in our record. We can also compare these results to evidence for MWP fires from other locations in BC (Gavin et al. 2003a,b; Hallett et al. 2003a,b). The presence of the MWP even in very different biogeoclimatic zones indicates its global effects.

As can be seen in Table 1, charcoal ages generally increase with depth, although there is an inversion at about 475 cm. We attribute the inversion to a debris flow off the adjacent slopes at about 13,500 ± 110 ^{14}C yr BP (i.e. 16,950–15,550 cal BP), subsequent to a fire recorded in the sediment at about that time. Horizons below this depth or ~11,000 cal BP yielded ^{14}C ages ranging from 7600 to over 12,000 cal BP. Considering all the dates, the oldest definite fire-reddened, but non-continuous, horizon is about 16,250 ± 700 cal BP. We interpret this lower charcoal to be redeposited and mixed by debris flow or fluvial transport. Detrital charcoal fragments below this horizon yielded ages ranging from 19,500 to 36,000 cal BP. These ages should be treated with considerable caution as they are based on sediments that had low yields of carbon (0.34–0.6% C). Nevertheless, they plot on the same age-depth curve as the other samples. This trend suggests that these old dates likely represent the true ages of the charcoal, and they are not mixtures of material of different ages, though the latter possibility cannot be ruled out. In the latter case, the low-carbon sediment ages are likely overestimates of the true age of the deposit, due to admixture of older material. The presence of charcoal of these ages suggests that this area may have been ice-free during much of the last 36,000 yr.

DISCUSSION

We have summarized our results as a cumulative plot of age probability distributions in Figure 6. This distribution was obtained by summing the probability ranges of all the calibrated ^{14}C ages. We summed the probability distributions derived from Calib 5.0 (Reimer et al. 2004), which is the same method employed by Meyer et al. (1995) and Pierce et al. (2004), except they used an older version of the calibration. This plot shows striking increases in fire at several periods (e.g. 2000–3000 cal BP, ~6000 cal BP, 7500–8000 cal BP, and 9500–10,000 cal BP). The probability shown on the vertical axis is an estimate of the instantaneous probability of fire, assuming all fires are sampled. This assumption may not be entirely accurate, since we need a large enough fire to trigger erosion of adjacent hillslopes to aggrade the fan deposits.

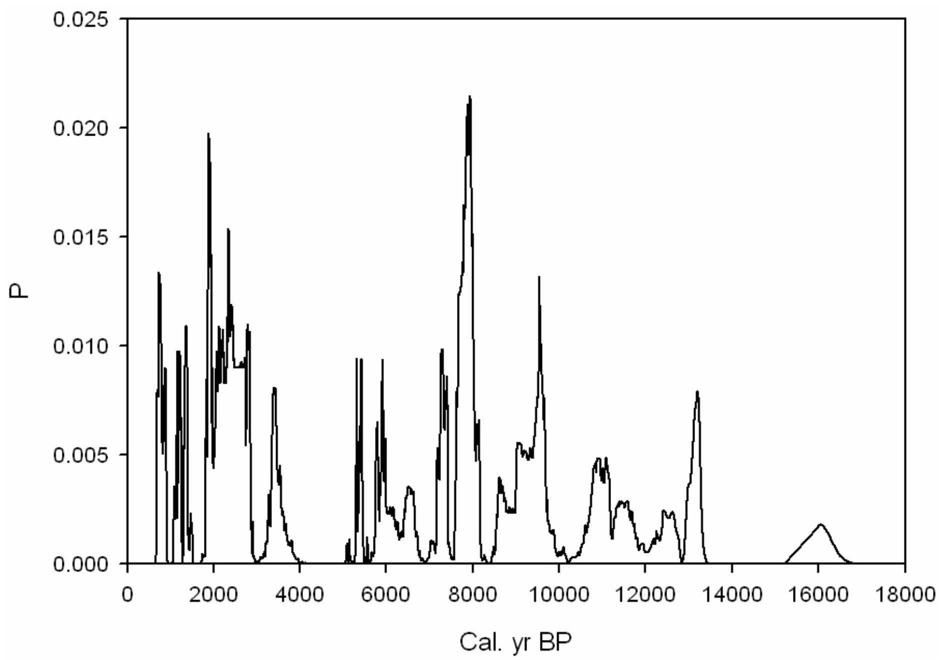

Figure 6 Plot of combined probability distributions (calculated from IntCal 98, Stuiver et al. 1998) for the last 16,000 yr of forest fires at Bear Flat, BC. The probability shown on the vertical axis is from the sum of the ^{14}C probability curves (Reimer et al. 2004).

The uppermost buried fire horizon (17–18 cm depth) gave an age of 913 ± 44 ^{14}C yr BP (920–760 BP [1 σ]; 930–730 cal BP [2 σ]) based on 2 independent determinations of 877 ± 35 and 966 ± 42 ^{14}C yr BP, where these dates were on separate discrete fractions of charcoal. Although the youngest age appears older than other records (e.g. Pierce et al. 2004; Sanborn et al. 2006), late-Holocene fire frequencies at Bear Flat are similar or lower than those inferred at other locations (Long et al. 1998; Hallett et al. 2003a; Millspaugh et al. 2000; Lertzman et al. 2002; Hallett and Walker 2000). It is possible that the youngest records have been removed by 20th century agricultural ploughing.

A lower rate of fires characterizes both the Younger Dryas period (11,000–12,900 cal yr, see Alley et al. 1993) and the preceding period. There is a marked increase in fire frequency to ~6 fires/kyr during the period 10,000 to 9000 cal BP, with a peak at ~9500 cal BP. No fire events are recorded for a short interval after 8500 cal BP. After 8300 cal BP, there is a considerable increase to ~10 fires/

10^3 yr, with a peak of ~13 fires/10^3 yr at 8000 cal BP. This is followed by a period of no fires and then fires at a rate of 4–6 fires/10^3 yr continues until ~5500 cal BP. The period of 4000–5000 cal BP records no fires in our record. Fires increase to an average of 8 fires/10^3 yr over the entire period of 2000 to 3000 cal BP, with a peak value of 12 fires/10^3 yr. The record from 800–2000 cal BP indicates a lower frequency of <4 fires/10^3 yr.

The early Holocene in western North America is a time of warm, dry conditions, which may explain the high fire frequency from 9000 to 8000 cal BP. A global cold event is known around 8200 cal BP, probably caused by the draining of Glacial Lake Agassiz and other large lakes at the time (Barber et al. 1999), which may have disrupted the North Atlantic thermohaline circulation. It is interesting to note a rapid increase in fire frequency just after that time. Climatic periodicity on a millennial scale has been observed in the North Atlantic record of ice-rafted debris (Bond et al. 1997), attributed to solar forcing (Bond et al. 2001; Braun et al. 2005) or oceanic circulation changes (Alley et al. 1999). We observed that only some ice-rafting events in the North Atlantic appear to coincide with or precede periods of increased fires in our record by ~200 cal yr.

Although several authors have asserted that decadal- and century-scale climate phenomena control fire recurrence (Masters 1990; Johnson 1992; Johnson et al. 1990; Johnson and Larsen 1991; Johnson and Wowchuk 1993), the charcoal record itself limits such interpretations. It is not possible to infer fire frequency at time scales of less than a century using ^{14}C dating of fossil charcoal. Most forest fires are generally considered to be "stand-replacing" fires occurring at intervals of ~200 yr, and this can be understood as the reason for the underlying rate of fires of about 4–5/10^3 yr during the Holocene.

It has also been noted by many authors that forest-fire frequency in some regions is climatically controlled, e.g. in Yellowstone (Meyer et al. 1995; Millspaugh et al. 2000), Idaho (Meyer et al. 2001), Oregon (Long et al. 1998), southwestern BC (Gavin et al. 2003b; Hallett et al. 2003a; Lertzman et al. 2002), and southeastern BC (Hallett and Walker 2000; Hallett et al. 2003b). This signal appears less marked in the tropics (Horn and Sanford 1992; Turcq et al. 1998) and in other mid-latitude regimes, such as in eastern Canada (Carcaillet et al. 2001) and New Zealand (Molloy et al. 1963).

Cumming et al. (2002) reported on persistent millennial-scale effects on moisture availability recorded at Big Lake, BC, in the semi-arid Cariboo region, some 500 km south of the Bear Lake site. It is also important to note recent studies, such as those of cyclic variations in an Alaskan lake, reported by Hu et al. (2003), which suggest millennial-scale periodicity. In other records from the northwestern USA, Whitlock et al. (2003) summarized the fire records observed in lake sediments from a number of lakes at 40–45°N. Several of these records showed millennial-scale periodicity, but they were not all in phase with the other records.

Records of forest fires at Yellowstone National Park indicated an increase in fire frequency at 9000 to 8200 BP (Millspaugh et al. 1998), followed by an abrupt reduction during the global cold event around 8200 cal BP (Barber et al. 1999). Millspaugh et al. (1998) suggested a trend related primarily to solar insolation, though more detailed dating suggests a link to millennial-scale phenomena (see also Meyer et al. 1995). The results of Meyer et al. (1995), discussed by Meyer and Pierce (2003), suggest an anti-correlation with Bond cycles and also a response to century-scale events such as the MWP and the Little Ice Age. Meyer and Pierce (2003) also compared the Yellowstone results to those from Idaho (Meyer et al. 2001). In this study, we note that the Bear Flat record shows evidence for fires during the MWP, but earlier fires appear to show a comparable millennial-scale trend to the Yellowstone results. However, when looking at the 2 records in detail, there is only a weak correspondence to some Yellowstone events such as about 2500, 6300, and 8200 cal yr, whereas other

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features are not correlated. This suggests that each region has its own response to long-term climatic forcing.

It is also interesting to consider the implications of this fire record for deglaciation in this region. The lowest fire-reddened soil horizon containing observable charcoal is dated to 15,644–16,659 cal BP, shown as a broad peak in Figure 4, which implies that this area was already deglaciated and at least partly forested at that time. This early deglaciation is consistent with other early dates on wood charcoal and terrestrial plant fragments from this region (Catto et al. 1996; Dyke et al. 2001). Catto et al. (1996) also estimated the area might have been ice-free by as early as 18,750–17,550 cal BP.

It is also important to consider the impact of aboriginal peoples, who cleared land with fire and have been in this area since about 13,000 cal BP (White and Mathewes 1986; Fladmark et al. 1988). Although studies in Europe have suggested that such fires would then not be linked to climate, other workers have suggested that fires started by humans can also be climate-linked, as periods of drought would tend to allow fires to spread.

CONCLUSIONS

We believe our record of forest fires from a continuous record from 1 site is important, since we study dates of fire-related debris from 1 small catchment, as opposed to the integration of several locations (e.g. Pierce et al. 2004). The record also shows a record of forest fires beginning in Late Glacial times, consistent with the deglaciation history of the region (Catto et al. 1996). We consider this forest-fire record to represent an important record of past climatic changes, and the record from Bear Flat shows a response to the Medieval Warm events; earlier, fires appear to have a millennial-scale variability. The record shows the effects of long-term periodicity in fire response, which must be linked to regional and global climatic conditions over the late Glacial and early Holocene. As more such records become available, it will be important to try to link these diverse expressions of climatic change with global models of climate and fire regimes over time.

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