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Holocene development of Boreal forests and fire regimes on the Kenai Lowlands of Alaska

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Abstract: Several studies have noted a relationship between vegetation type and fire frequency, yet despite the importance of ecosystem processes such as fire the long-term relationships between disturbance, climate and vegetation type are incompletely understood. We analysed pollen, plant macrofossils and sedimentary charcoal from three lakes within the Kenai lowlands to determine postglacial relationships between disturbance, climate and vegetation for the Boreal forest of southwest Alaska. An herb tundra was established in the lowlands following deglaciation by 13 000 cal. BP. *Salix*, *Alnus* and probably *Betula kenaica*, expanded in the area after 10 700 cal. BP, followed by *Picea glauca* by 8500 cal. BP. *Picea mariana* became established by 4600 cal. BP. The early Holocene was probably the driest time during the postglacial, as determined by aquatic plant macrofossils and climate models. Lake levels reached near-modern conditions by at least 8000 cal. BP. Mean Fire Intervals (MFI) were longest during the shrub–herb tundra phase (138 ± 65 yr), decreased after expansion of *B. kenaica*, *Salix* and *Populus* (77 ± 49 yr) and *Picea glauca* (81 ± 41 yr), and increased again with the arrival of *P. mariana* (130 ± 66 yr). Unlike previous studies, our data demonstrate the highest fire frequencies during the early to mid-Holocene and less frequent fire during the late Holocene when *P. mariana* forests dominated the lowlands. Early Holocene forests of *P. glauca* and *B. kenaica* existed in summers that were longer and drier than today, while the increasingly wetter and cooler climates of the late Holocene probably hindered forest fire around Paradox Lake, perhaps because of less frequent summer drought.

Key words: Boreal forest, charcoal analysis, climate change, fire history, vegetation history, Holocene, Alaska.

Introduction

Our understanding of vegetation development in Alaska has advanced rapidly during the last two decades (Anderson *et al.*, 2004). Much debate has centred on determining the spatial and temporal history of modern boreal forest development and its relationship to Holocene climatic changes. Lateglacial and early Holocene forests were often dominated by *Populus*, then *Alnus* and *Salix*, either as woodlands or in riparian galleries (Ager, 1983; Brubaker *et al.*, 1983; Hu *et al.*, 1993; Anderson *et al.*, 1994; Mann *et al.*, 2002). The modern Boreal forest developed time transgressively, however. *Picea glauca* was probably the first Boreal conifer to spread from east to west across central Alaska, most likely between *c.* 9000 and 8000 cal. BP (Anderson and Brubaker, 1993, 1994; Brubaker *et al.*, 2001), followed by *Picea mariana* at least 2000 years later (Anderson *et al.*, 2004).

However, our understanding of the role of ecosystem disturbance in vegetation development has lagged far behind.

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Even though climatic influences on wildfire behaviour in the Boreal forest have been well-documented (ie, Johnson, 1992; Flannigan *et al.*, 2003), the influences on fire occurrence and extent in Alaska are complex (Kasischke *et al.*, 2002). Perhaps because of this the limited data on palaeo-fire occurrence in Alaska are contradictory. Some authors have suggested that higher fire event frequencies occurred in the early Holocene (Earle *et al.*, 1996) when models suggest climate was warmer and drier than today (Kaufman *et al.*, 2004a), while others have documented higher frequencies for the late Holocene (Hu *et al.*, 1993, 1996; Lynch *et al.*, 2003, 2004) when climate became wetter and cooler.

Discrepancies in fire histories may be related to climatic factors. Carcaillet *et al.* (2001) showed the importance of climate in determining fire, since changes in species with more combustible foliage did not accompany significant changes in fire occurrence during the Holocene. Alternatively, differences may be moderated by the timing of species immigration or by soil development or edaphic conditions. Differences in fire history corresponded with a change from conifer- (*Picea*–*Pinus*; greater fire occurrence) to hardwood-dominated (lesser fire occurrence) forests in an early Holocene sequence from northern New York (Clark *et al.*, 1996). This suggests the relative importance of forest type over climate conditions for determining fire event frequencies.

In the present study we used high-resolution sedimentary charcoal, pollen and plant macrofossils from three sites in the lowlands of the Kenai Peninsula to answer the following questions: what was the timing of development of the *Picea* (boreal spruce) – *Betula* (birch) forest over the last *c.* 13 000 years in this maritime location? What is the history of fire disturbance, and how does it compare with other sites in Boreal forest in Alaska? What is the relative importance of climatic versus species composition factors in determining fire history? What can the fossil assemblages tell us about the climate history of the region? This study also contributes to our understanding of the characteristics of climate change in the subarctic, projected to be among the regions most vulnerable to global warming (Serreze *et al.*, 2000; Moritz *et al.*, 2002).

Location of sites

The Kenai Peninsula includes the Kenai Mountains in the east and the Kenai lowlands in the west (Figure 1). The central core of the Kenai Mountains (over 1 900 m elevation) is dominated by the Harding Ice Field. Elevations of the lowlands rarely exceed 550 m and are mostly below 300 m (De Volder, 1999). Repeated glacial advances from the Kenai Mountains and the Aleutian Range to the west across Cook Inlet formed the lowland physiography during the late Pleistocene (Reger and Pinney, 1997).

Today, climate of the Kenai Peninsula is boreal maritime (De Volder, 1999), more continental in the central peninsula, and more oceanic along the coast. Annual precipitation at Kenai, Alaska (60° 34′N, 151° 15′W) is *c.* 484 mm (National Climate Data Center – United States Historical Climatology Network) (NCDC–USHCN), 1998). Mean July and January temperatures are 12.3°C and −10.9°C, respectively (Leslie, 1989).

Our longest record comes from Paradox Lake, *c.* 10 km north of Sterling in the Kenai lowlands (Figure 1). The lake occupies a glacially deepened trough that may have been a postglacial spillway. Maximum depth of the lake is *c.* 15.8 m (Figure 2), and the lake is meromictic. Sediment cores also come from Portage and Arrow Lakes, *c.* 16.6 and 19.5 km, respectively, from Paradox Lake (Figure 1). These cores come from <3 m depth.

Typical vegetation of the lowlands and in the vicinity of all three lakes is *Picea glauca* and *Betula kenaica* on well-drained soils and slopes, and *P. mariana* on more poorly drained lowland flats. Additional upland trees and shrubs around Paradox Lake include *Populus tremuloides*, *Alnus crispa*, *Sambucus racemosa*, *Rosa acicularis*, *Viburnum edule*, *Linnaea borealis*, *Rubus* sp., *Echinopanax horridum*, *Ribes* sp. and *Ledum palustre*. Plants common in moist areas around the lake include *Salix* sp., *Myrica gale*, *Menziesia ferruginea*, *Spiraea Beauverdiana*, *Betula nana*, *Streptopus amplexifolius*, *Lycopodium* sp., *Equisetum silvaticum* and *E. arvense*. Nomenclature follows Hultén (1968) and Flora of North American Editorial Committee (FNAEC, 1997).

Methods

At Paradox Lake we obtained a Livingstone core (885 cm long) and a short core (to 70 cm length) in June 1998. The two cores were matched based on a similar tephra layer in the upper *c.* 45 cm of each core. Short cores from Portage and Arrow Lakes were obtained in June 1995. Sediment stratigraphy (including tephra; de Fontaine, 2003) was determined by visual inspection and/or petrographic analysis. Magnetic susceptibility was determined by a Bartington MS2E meter at 5-mm intervals.

One cubic centimetre of sediment was processed for pollen (Fægri *et al.*, 1989) including addition of *Lycopodium* tracers for pollen concentration calculation. Residues were stained, suspended in silicone oil, and examined at 400 ×, with comparison to the modern pollen reference collection at the Laboratory of Paleoecology (LOP). Pollen of *Picea glauca* and *P. mariana* was differentiated as in Hansen and Engstrom (1985). Pollen data were clustered using CONISS (Grimm, 1987), and graphed using Tilia View.

Plant macrofossils were sieved from *c.* 100 cm^3 of sediment at 10- to 20-cm intervals (Paradox) or from each successive centimetre of depth (Arrow and Portage). Needle fragments, seeds and other macrofossils were identified under a binocular microscope.

High resolution sedimentary charcoal analysis followed Millspaugh and Whitlock (1995), using 5 cm^3 subsamples from each linear centimetre of the core length. We analysed charcoal accumulation rates (CHAR) as a time series and decomposed the record into background and peaks components using Charcoal Analysis Programs (CHAPS) (Long *et al.*, 1998). The background component considers variations in overall charcoal production and sedimentation. The peaks component represents the charcoal input from a fire event within or near the watershed, where a fire event is defined as one or more fires occurring within the sampling interval.

The CHAR time series is created by dividing charcoal concentration values by deposition times (Long *et al.*, 1998). When a CHAR value exceeds the background by a selected threshold ratio (eg, 1.05, 1.1, 1.2) a charcoal peak (fire event) is recorded. We compared the fire interval statistics for three scenarios (many inferred fires using 300–1.05, moderate fires using 300–1.2, few fires using 500–1.2) from CHAPS to see how the fire intervals might vary. A 2000-yr smoothing function was used to plot the frequency of fire events per 1000 years (Long *et al.*, 1998).

AMS and whole sediment radiocarbon ages were calibrated to calendar ages (Table 1) using CALIB version 4.4 (Stuiver

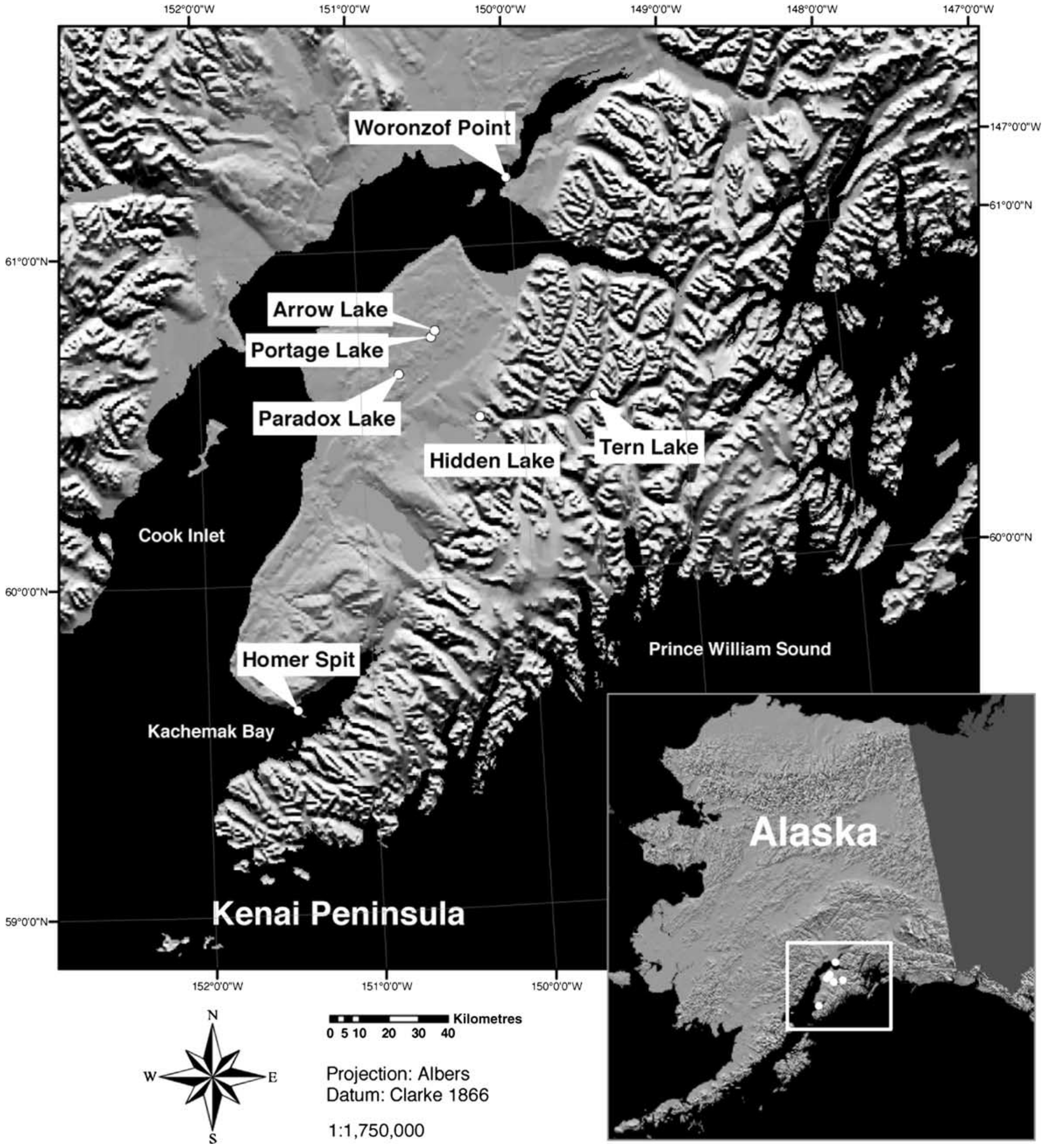

Figure 1 Location of the Kenai Peninsula, Alaska. Also shown are locations of Paradox, Arrow and Portage Lakes (this study); Hidden Lake (Ager, 1983); Point Woronzof (Ager, 1983); Homer Spit (Ager, 2000); and Tern Lake (Ager, 2001)

et al., 1998). ^{210}Pb and ^{137}Cs ages were measured by gamma spectrometry (R. Ku, personal communication, 2004).

Results and discussion

Stratigraphy and chronology

The Paradox Lake sediments are bedded throughout, have high organic content, and are generally alternating grey to black and brown and dark-brown gyttja and clayey-silt layers (Figure 3). Magnetic susceptibility is generally highest below *c.* 780 cm depth.

The Paradox Lake chronology is based upon a composite of the ^{210}Pb profile for the upper portion, and the AMS ^{14}C ages for the remainder of the core (Table 1). We excluded Beta-125980, believing this to be anomalously old, since *Picea* needles dated separately from the same interval were over 2000 years younger (Table 1). Chronology for the short core was based on measurements of ^{210}Pb from the upper 25 cm, and identification of the ^{137}Cs peak (AD 1963). Our identification of this peak in the core gives us the linear sedimentation rate averaged over the past ~40 years. For determining the average sedimentation rate over the past ~100 years, we used the slope of a semi-log plot of excess ^{210}Pb versus depth in the core. The resulting sediment accumulation rate of 2.5 ± 0.5 mm/yr determined in the upper 10 cm was applied down to 37 cm depth, and verified by comparison with the known fire history of the area (see below).

The sediment accumulation curve (Figure 4) consists of the linear interpretation of sediment accumulation above 37 cm matched to a sixth-order polynomial (using the median probability values (Telford *et al.*, 2004) of the 11 calibrated age dates) below 37 cm. We chose a sixth-order polynomial because other polynomials poorly approximated ages between 550 and 800 cm depth.

The upper *c.* 34 cm of Portage Lake sediments consist of gyttja with interspersed sands, while below this to 59 cm is mostly pure gyttja (Figure 5). The record is *c.* 9 400 cal. yr long (Table 1). The Arrow Lake sediments are primarily gyttja, but

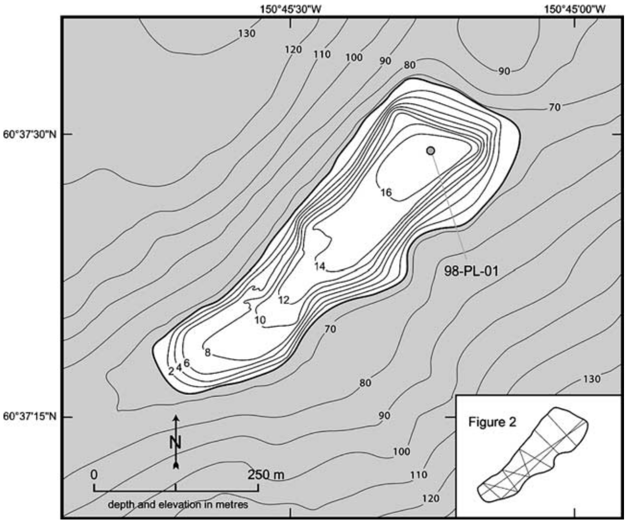

Figure 2 Bathymetry of Paradox Lake, with site of cores taken from the maximum depth of the lake. Lines on inset are the location of transects used to construct bathymetry

include sandy layers and layers with coarse organic fragments (Figure 5). This record is *c.* 9 500 cal. yr BP long (Table 1).

Palaeobotanical record

Paradox Lake

Zone 1 (prior to *c.* 10 700 cal. BP) pollen spectra are dominated by *Betula* (to 69%), while Poaceae (to 13%), Cyperaceae (to 11%), and *Artemisia* (to 6%) are at their postglacial maxima (Figure 6a). We consider it likely that most *Betula* are shrub birch, such as *B. nana* or *B. glandulosa*, rather than tree birch, *B. kenaica* (see Clegg *et al.*, 2005). *Salix* (to 12%) pollen occurs throughout the zone, while *Populus* (to 3.5%) is found in the middle. We interpret the local environment as shrub tundra.

In Zone 2 (*c.* 10 700 to 8500 cal. BP) herbaceous and sub-shrub species (ie, *Betula*, Ericaceae, Cyperaceae, Poaceae (Figure 6a) decline. *Salix* (to 24%) increases, followed by *Populus* (to 26%), then *Alnus* (to 37%). By the zone's end, *Betula* increases again. These changes are consistent with successive immigrations of large shrubs and common deciduous trees into the Paradox Lake area. *Botryococcus* and *Chara* increase (Figure 6b), along with *Najas* and *Nuphar* (Figure 7a), indicating lowered lake levels during the early Holocene.

By Zone 3 time (*c.* 8500 to 4600 cal. BP) *Betula* and *Picea* pollen percentages are consistent with *Picea glauca* – *Betula* woodland (Anderson and Brubaker, 1986) on the uplands around the lake. *Sphagnum* spores (Figure 6b) increase, and suggest establishment of boggy conditions on the lake perimeter.

Zone 4 (*c.* 4600 cal. BP to present) pollen and spore assemblages suggest that the *Picea glauca* – *Betula kenaica* forests persisted in uplands around the lake throughout the remainder of the Holocene. However, by *c.* 4600 cal. BP *Picea mariana* pollen percentages increase, suggesting the establishment of *P. mariana* in lowlands around the lake. This coincides with a second increase in the *Sphagnum* spores. While the former may be related to a late migration to the region, the latter suggests further development of boggy conditions locally.

Portage and Arrow Lakes

Macrofossils are dominated by Cyperaceae, *Potamogeton* and *Nuphar* at Portage Lake from the core bottom to *c.* 8000 cal. yr ago (Figure 7b). At Arrow Lake, a similar assemblage of *Nuphar* and *Potamogeton* remains is found until after *c.* 8100 cal. BP (Figure 7c). These shallow-rooted aquatics subsequently decline in both records. By *c.* 9000 and 8700 cal. BP, *Betula*

Table 1 Radiocarbon dates and calendar age ranges for Paradox, Portage and Arrow Lakes, Alaska

Lake	Lab no.	Depth (cm)	^{13}C/^{12}C Ratio	^{14}C yr BP	Max and min of 2 sigma cal. age range	Median probability used in Age Model[a]	Date type	Materials dated
Paradox	AA-45098[b]	81.5	– 27.9	1373 ± 47	1177–1385	1290	AMS	Wood, charcoal, *Betula* fruit, *Picea* needles
	AA-45099	97.5	– 28.0	1225 ± 45	1012–1265	1147	AMS	Wood, charcoal, *Betula* fruit, *Picea* needles
	AA-45100	165.0	– 28.9	2603 ± 41	2495–2837	2743	AMS	Wood, charcoal, *Betula* fruit, *Picea* needles
	AA-45101	193.0	– 28.4	2969 ± 51	2969–3321	3140	AMS	Wood
	AA-45102	289.0	– 26.2	4054 ± 43	4418–4806	4529	AMS	*Picea* needles, wood, *Betula* fruit
	AA-45103	311.0	– 25.8	4565 ± 45	5047–5447	5183	AMS	Charcoal, wood, *Betula* fruit
	AA-38445	344.5	– 27.8	4917 ± 88	5471–5893	5663	AMS	*Picea* needles
	AA-38446	399.5	– 27.4	5598 ± 76	6204–6616	6381	AMS	*Picea* needles
	AA-38447	552.5	– 28.5	7100 ± 59	7761–8104	7901	AMS	*Picea* needles
	AA-45104	799.0	– 30.4	9974 ± 65	11 203–11 907	11 416	AMS	Charcoal, wood
	Beta-177159	873.0	– 28.8	10 970 ± 70	12 664–13 160	12 994	AMS	Wood
	Beta-125980[b]	864.0–874.0	– 30.3	13 250 ± 80	15 016–16 465	15 892	AMS	Bulk sediment
Portage	AA 58539	17.0–18.0	– 27.7	2227 ± 37	2149–2335	2233	AMS	*Picea* needles
	AA 58540	25.0–26.0	– 28.0	3813 ± 39	4087–4405	4203	AMS	*Picea* needles
	AA 58541	45.0–46.0	– 25.9	7994 ± 48	8650–9010	8863	AMS	*Nuphar* seeds
	AA 58542	59.0–60.0	– 25.6	8355 ± 55	9143–9517	9372	AMS	*Nuphar* seeds
	Beta-117013	56.0–61.0	– 25.0	9160 ± 190	9707–11 061	10 343	Standard	Bulk sediment
Arrow	AA 58544	15.0–16.0	– 28.3	4675 ± 48	5308–5578	5406	AMS	*Picea* needles
	AA 58543	28.0–29.0	– 26.8	8050 ± 48	8719–9232	8937	AMS	*Nuphar* seeds
	Beta-117012	45.0–50.0	– 25.0	8800 ± 210	9332–10 402	9873	Standard	Bulk sediment
	AA 58545	49.0–51.0	– 26.3	8518 ± 49	9433–9551	9510	AMS	*Nuphar* seeds

[a] Median probability values from CALIB 4.4 were chosen for construction of the age–depth curve using Stuiver *et al.* (1998).
[b] Excluded from age model.

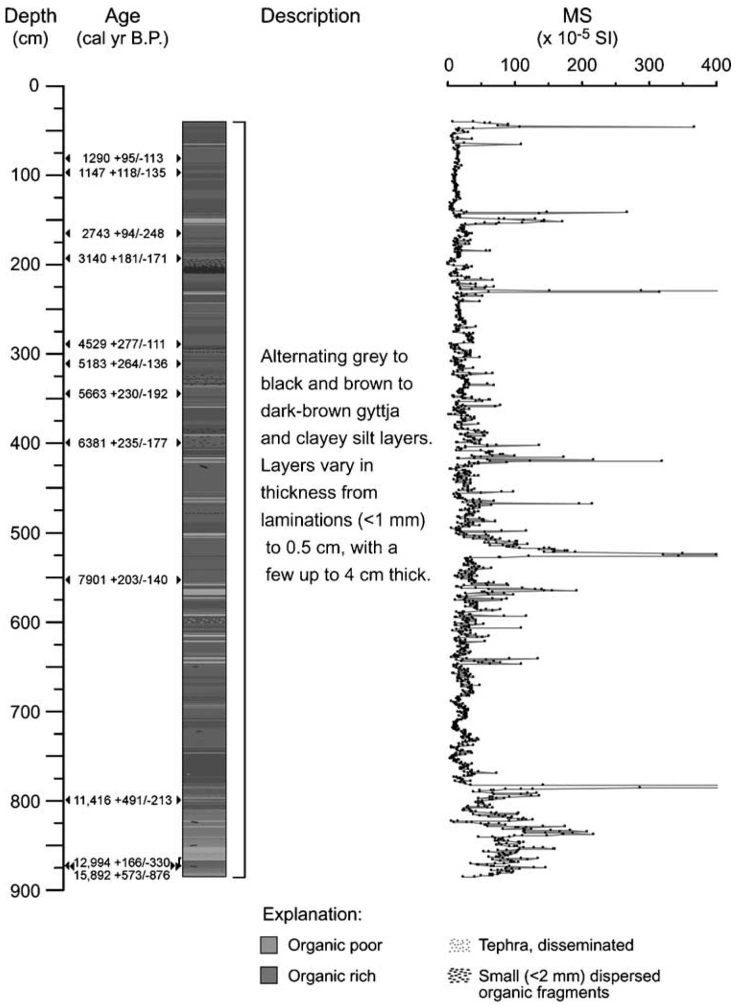

Figure 3 Paradox Lake core stratigraphy and magnetic susceptibility, with location of radiocarbon dates

fruits and *Picea* needle fragments are found at Portage and Arrow Lakes, respectively. We interpret the earliest portion of the record as recording lowered lake levels prior to and into the establishment of the *Picea glauca* – *Betula kenaica* forests there.

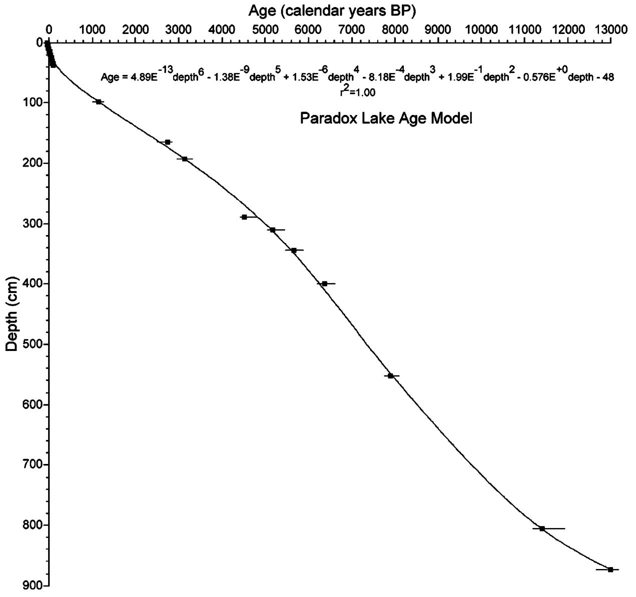

Figure 4 Paradox Lake age–depth relationship, with a sixth order polynomial

Vegetation and climate history of the Kenai Peninsula

Few well-dated pollen sites such as Paradox Lake have been analysed from the Kenai Peninsula. A herbaceous tundra was present until *c.* 16 000 cal. BP at Hidden Lake, persisting to *c.* 14 750 cal. BP at Circle Lake and Point Woronzof (Rymer and Sims, 1982; Ager, 1983, 2000). Subsequently, a shrub *Betula*–herb tundra existed at the northern sites (Point Woronzof and Hidden Lake) to *c.* 11 250 cal. BP, and in the Kachemak Bay area to *c.* 10 600 cal. BP (Ager, 2000). After immigration of *Populus* and *Salix* at the more northerly sites, *Alnus* arrived throughout the Peninsula by *c.* 10 600 cal. BP, mixing with *Betula* and ericaceous shrubs or grass at the Kachemak Bay sites (Ager, 2000), or *Salix* and other shrubs at the Kenai Mountain and upper Cook Inlet sites (Ager, 2000, 2001).

Boreal *Picea* – probably *P. glauca* – immigrated into the northern Kenai Peninsula perhaps as early as *c.* 8750 cal. BP at Point Woronzof and Hidden Lake (Ager, 2000). *Picea* (again, probably *P. glauca*) and *Betula* invaded the Tern Lake area from the Kenai Lowlands to the west by *c.* 6300 cal. BP. Immigration of *Picea* was delayed at the Kachemak Bay sites until *c.* 4000 cal. BP.

The vegetation histories recorded at Paradox, Arrow and Portage Lakes are transitional between those previously inferred from northern and southern sites. At Paradox Lake, a shrub *Betula*–herb tundra gave way to *Populus* and *Salix* by 10 600 cal. BP. Successive immigrations occurred in the early Holocene, first by *Alnus* (*c.* 9600 cal. BP) then *Betula* (cf. *kenaica; c.* 8500 cal. BP). *P. glauca* also arrived by *c.* 8500 cal. BP, creating a mixed boreal *Picea*–hardwood forest. By *c.* 4500

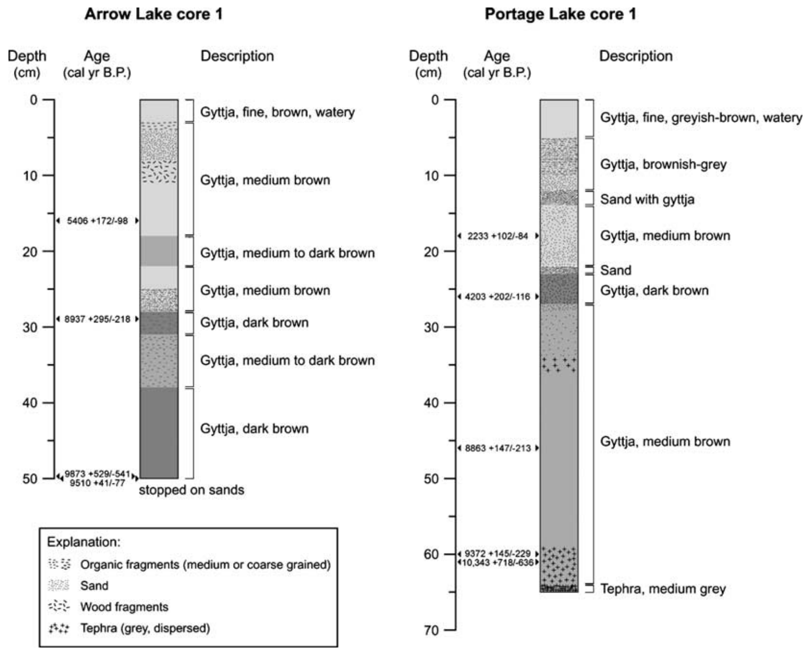

Figure 5 Core stratigraphy of Arrow and Portage Lakes short cores, with location of radiocarbon dates

cal. BP, however, *P. mariana* became established around Paradox Lake, and remained important in the lowland flora up to the present.

The spread of Boreal forest into the Kenai Peninsula and surrounding areas was fostered by climates that were warmer and drier than present (Heusser *et al.*, 1985). Models suggest maximum Northern Hemisphere summer solar insolation occurred *c.* 12 000 to 10 000 years ago (Kutzbach *et al.*, 1998), with empirical data suggesting the Holocene thermal maximum occurred *c.* 11 000 to 9000 cal. BP (Kaufman *et al.*, 2004a). Lowered lake levels also suggest drier early Holocene climates in Interior Alaska (Abbott *et al.*, 2000; Barber and Finney, 2000; Edwards *et al.*, 2000, 2001). Remains of wetland and rooted aquatic plants dominate the macrofossil assemblage until *c.* 8000 years ago in our shallow-water Arrow and Portage Lake cores, suggesting lower lake levels here as well.

By the late Holocene, expansion of *Picea mariana* in the lowlands was contemporaneous with cooler and wetter climate (Heusser *et al.*, 1985; Ager, 2000), as summer insolation decreased (Berger and Loutre, 1991) and Neoglacial advances occurred (Kaufman *et al.*, 2004b). Locally, increasing soil moisture is indicated by expansion of *Sphagnum* on the valley floor around Paradox Lake.

Fire history record

Previous fire history research on the Kenai Peninsula

De Volder (1999) used a combination of stand-age mapping, fire-scars on living trees and ageing of burn poles to reconstruct fire history since AD 1708 in lowland black spruce forests. The AD 1947 Sterling fire burned the watersheds of Portage and Arrow Lakes but not Paradox Lake. An AD 1849 fire occurred at Paradox and Portage Lakes, while an AD 1888 fire burned at both Arrow and Portage Lakes. The AD 1969 Kenai fire (*c.* 32 000 ha) burned to within several kilometres of Paradox Lake (Alaska Fire Service, 1999). Fire return intervals in black spruce forests of the Lowlands have ranged from 25 to 185 years, with a mean of 89 ± 43 years (De Volder 1999).

Berg and Anderson (2006) analyzed the ages of charcoal layers from soil pits and throw mounds throughout the western Kenai lowlands. Clusters of the 17 charcoal radiocarbon dates suggest fires burned around Paradox Lake *c.* AD 1835, 1640, 1455, 1265, 670 and 120. The most recent charcoal age of AD 1835 probably represents the most recent fire in AD 1849. Calculated fire return interval for the whole lowland data set approximates 325 years for the entire series, but only 190 years since the thirteenth-century fire. Lynch *et al.*'s (2004) Rock Lake record, also in the Lowlands, is very similar to the Paradox Lake soil charcoal data, giving a pre-twentieth century fire return interval of 194 years.

Calibration of the sedimentary record

For the upper sediments, maximum values for CHAR peaks occur at 3 cm (AD 1987), 7 cm (AD 1969), 10 cm (AD 1958), 18 cm (AD 1926), and 35 cm (AD 1858) (Figure 8). The peak at 7 cm may be associated with the 32 000-ha ad 1969 fire that burned to within 2.4 km of Paradox Lake (De Volder, 1999). We did not use this peak to calibrate our reconstruction scenarios because the fire was too far from the lake site. The peak at 10 cm may be the AD 1947 fire, while the 35-cm peak undoubtedly corresponds to the AD 1849 fire that burned around the lake and represents the best calibration peak for reconstructing fire event frequency. The later two ages suggest that our chronology may be in error by several years. We know of no fire that burned around the lake corresponding to the 3 and 18 cm depth peaks. Our ability to match most of the peaks in the short core with known fire events within the watershed provides confidence in our interpretation of the longer record. Even so, some charcoal peaks may be derived from fires that burned close to, but not directly around, the lake (Whitlock and Millspaugh, 1996). To decrease the potential for identifying charcoal peaks in our record created by distant (non-local) fires, we used soil charcoal evidence from the AD 1849 fire, and other fires listed above, to select appropriate threshold ratios for our analysis. Our goal was to identify parameters that verify CHAR peaks derived mainly from local watershed fire episodes at the top of the core where fire evidence overlaps. Parameters used for the fire frequency reconstruction verified all local fires and minimized the identification of non-local peaks in the top 2000 years of CHAR (Gavin *et al.*, 2003; Hallett *et al.* 2003).

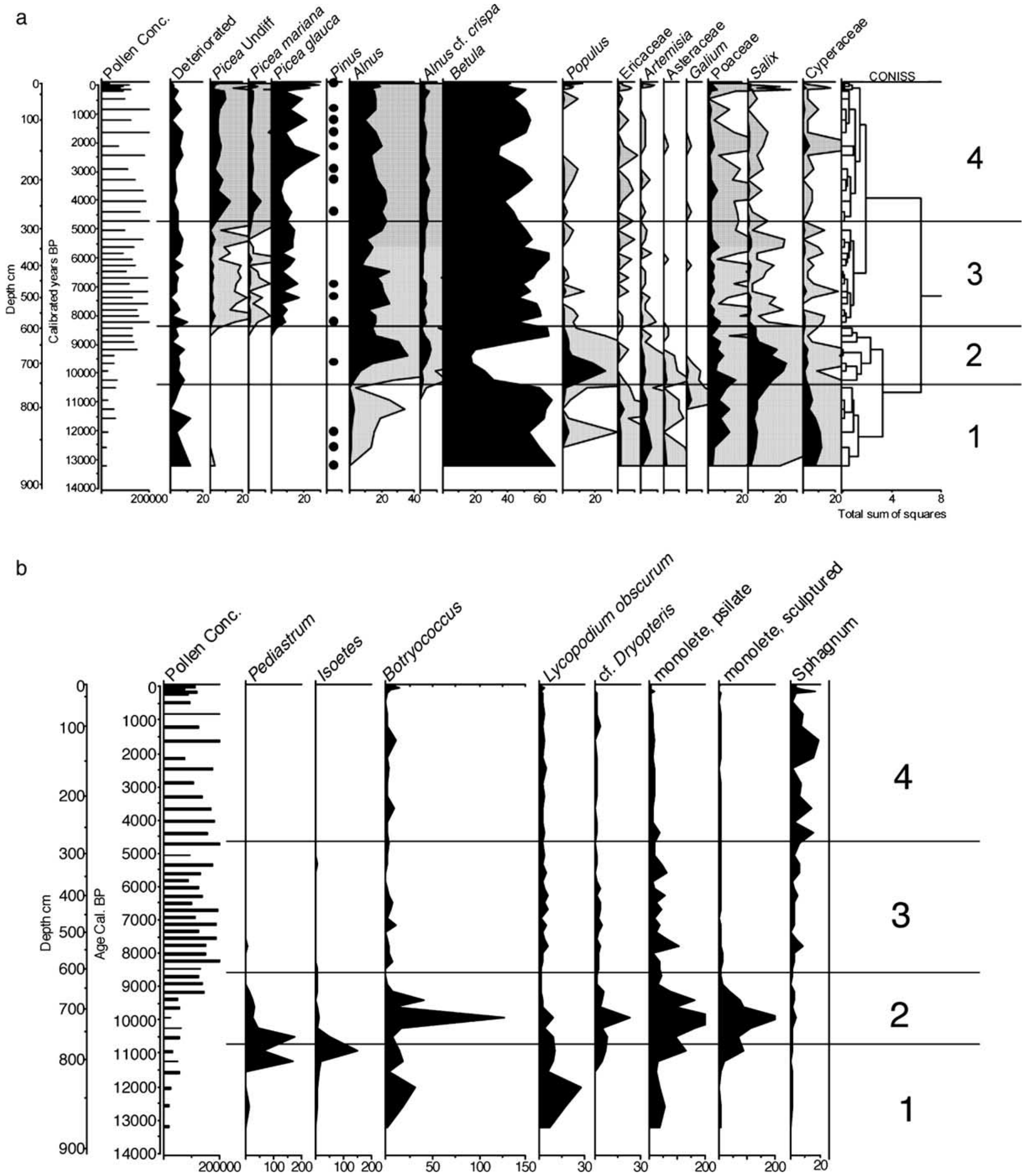

Figure 6 (a) Terrestrial pollen percentages from Paradox Lake record. Silhouette is 10 × pollen percentage. Pollen zones were determined objectively using the cluster analysis program CONISS (Grimm, 1987). (b) Spore percentages from Paradox Lake record

Calculation of mean fire intervals and fire event frequencies

The three CHAPS scenarios resulted in similar fire interval estimates for each pollen zone (Table 2). We selected the middle scenario because it conveyed the common trends in the Holocene fire interval data and corresponded well with known fire evidence in the watershed. In all the CHAPS scenarios, MFI (mean fire interval) was longest for Zone 1, a period of tundra. Mean values ranged from 124 to 172 yr between fire events. MFI for Zone 4 – mixed Boreal *Picea* zone – was also long, varying from 122 to 134 yr. MFIs for Zone 2 (mixed shrub and hardwoods), and Zone 3 (*Picea glauca–Betula* forest), were nearly identical, 77–82 and 77–85 yr, respectively (Table 2). The similarity between fire interval statistics based on three CHAPS scenarios suggests that the CHAPS estimates of Paradox Lake fire intervals are robust.

We used the Kolomogorov-Smirnov two-sample test to test whether fire interval distributions differed between pollen zones (Table 3). Zones 1 and 4 were significantly different from Zones 2 and 3. Zones 1 and 4 were not significantly different from each other, even though they occurred during the late Pleistocene and late Holocene when climates and vegetation types were very different. Fire intervals in Zones 2 and 3 from the early and mid-Holocene were also not significantly different (Table 3).

Based on our comparison of fire peaks in the sediment record with known fires on the Peninsula we believe that the sedimentary charcoal method somewhat overestimates local fires because it represents a complex spatial aggregation of fire events around the site, and thus provides a maximum fire event frequency. On the other hand, processes that limit preservation of charcoal in soil profiles tend to cause an underestimation

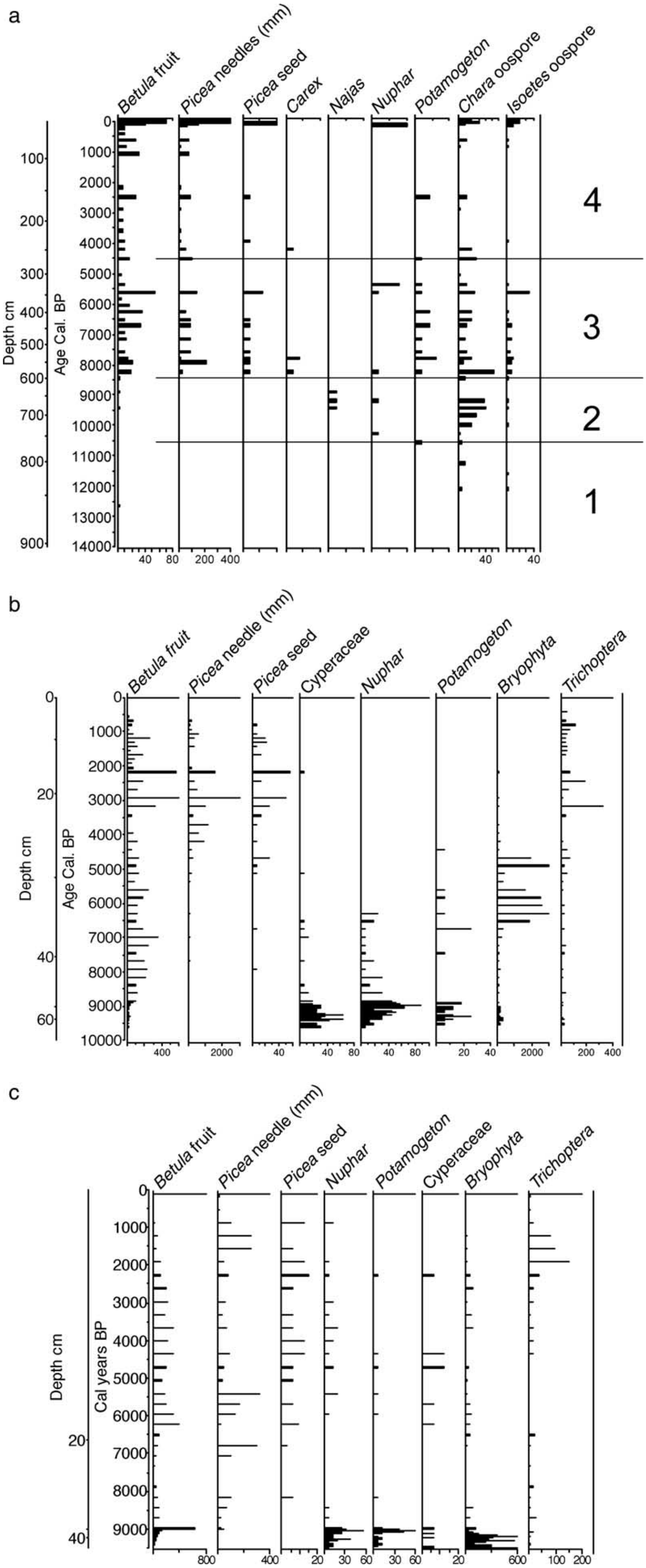

Figure 7 (a) Plant macrofossils from Paradox Lake core. (b) Plant macrofossils from Portage Lake short core. (c) Plant macrofossils from Arrow Lake short core

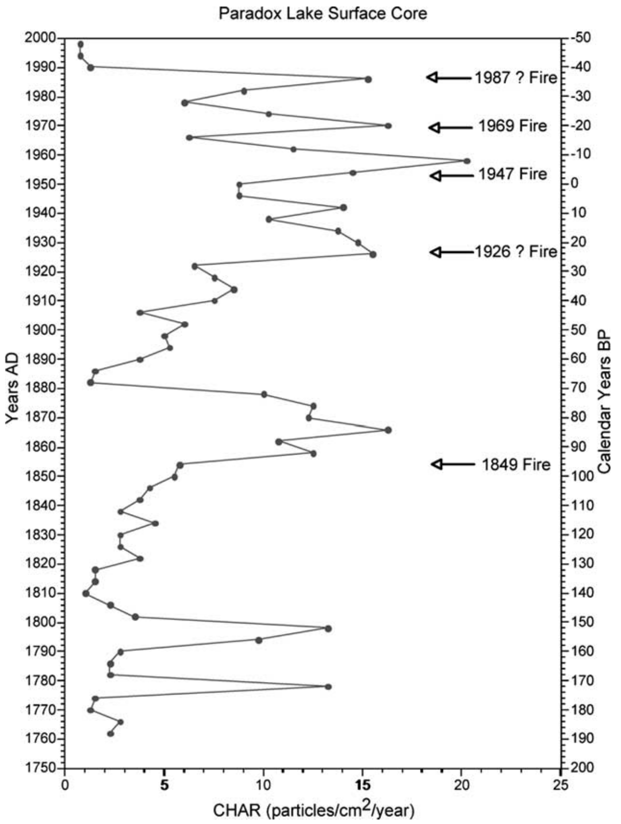

Figure 8 Charcoal accumulation rates from the Paradox Lake short core with a chronology in cal. yr BP and years AD from ^{210}Pb data. Local fires of known ages (ie, 1849 fire) are located with respect to the inferred ^{210}Pb chronology. Charcoal peaks without a documented local fire (ie, 1926?) are also shown

of local fires (Gavin, 2001, 2003; Lertzman *et al.*, 2002; Gavin *et al.*, 2003; Hallett *et al.*, 2003), thus providing minimum local fire event frequencies.

Fire history

The high-resolution charcoal data allowed for complete identification of most fires considering the century-scale fire intervals that characterize the current forest type around Paradox Lake (Yarie, 1981; Larsen, 1997). A fire event frequency (FEF) of six to ten fires/1000 yr characterizes Zone 1 (Figure 9), when pollen evidence suggests that herb tundra vegetation surrounded the lake. Tundra fires are mostly rare events (Wein, 1976; Payette *et al.*, 1989). Low FEF during the early postglacial may have been due to sparse vegetation leading to relatively light fuels necessary to carry fire and deposit charcoal in the lake.

When large shrubs and trees were established around Paradox Lake during Zone 2, FEF increased substantially. Higher FEF (10–13 fires/1000 yr; maximum of 14 fires/1000 yr) occurs with the expansion of *Betula* at the end of the zone. Palaeoclimate reconstructions (Kutzbach *et al.*, 1998; Edwards *et al.*, 2001) suggest that this was the warmest and driest period of the Holocene.

With the expansion of *Picea glauca* and *Betula* around 8500 cal. BP, FEF reaches the highest values of the record (11–14 fires /1000 yr) and remains high until *c.* 4600 cal. BP. We believe that relatively high FEF resulted from a combination of increased flammable coniferous biomass in the uplands and continuation of relatively warm summers as shown from modelled data.

Coincident with the arrival of *Picea mariana*, FEF drops to 5–8 fires/1000 yr. Today *P. mariana* grows in a relatively narrow zone in boggy areas around the lake. Development of a peripheral wetland may have reduced the overall flammability around the lake during the last 4 600 years, even while the uplands remained dominated by *P. glauca* and *Betula*. Alternatively, the expanded wetland may have hampered the movement of charcoal via traction from uplands to the lake.

The Paradox Lake record shows some similarities with other Alaskan studies, but also considerable differences. These differences may be a function of several factors, including the effect of vegetation type or climate change on frequencies and

Table 2 Comparison of fire interval data for three scenarios of parameters used in CHAPS

Age interval (yr BP)	Pollen Zone	Mean ± s.d. for CHAPS parameters (window width-threshold ratio)					
		300–1.05	*N*	300–1.2	*N*	500–1.2	*N*
−48–4600	4	122 ± 56	38	130 ± 66	35	134 ± 72	34
4600–8500	3	77 ± 44	52	81 ± 41	49	85 ± 52	47
8500–10700	2	79 ± 43	27	77 ± 49	27	82 ± 57	26
10 700–13 500	1	124 ± 55	22	138 ± 65	20	172 ± 90	16
All fires −48–13 500		97 ± 54	139	102 ± 60	131	109 ± 72	123

Table 3 Comparisons of (300–1.2) fire interval summary statistics from different time periods and by Kolomogorov–Smirnov 2-sample tests

Age interval (yr BP)	Fire intervals			Kolomogorov–Smirnov 2-sample tests (yr BP)[a]			
	N	mean ± s.d.	(Range yr)	– 48–4600	4600–8500	8500–10 700	10 700–13 500
– 48–4600	35	130 ± 66	(40–270)	–	$p < 0.01$	$p < 0.01$	NS
4600–8500	49	81 ± 41	(30–190)	$p < 0.01$	–	NS	$p < 0.05$
8500–10 700	27	77 ± 49	(30–220)	$p < 0.01$	NS	–	$p < 0.05$
10 700–13 500	20	138 ± 65	(50–290)	NS	$p < 0.05$	$p < 0.05$	–
all – 48–13 500	131	102 ± 60	(30–290)				

[a] Table entries are KS 2-sample tests with no difference being NS where $p > 0.05$. Significant differences in fire interval data are shown at the $p < 0.05$ or 0.01 level.

patterns of burning, potential differences in charcoal delivery to the lake, or different methodologies in each study. For instance, Lynch *et al.* (2003) suggested that vegetation history was important in determining fire history. At Dune Lake, early Holocene *Picea glauca–Betula papyrifera* forests burned less frequently than late Holocene *P. mariana* forests. Further, calculated fire event frequencies were high in late Holocene forests around Moose and Chokasna Lakes, also dominated by *P. mariana* forests (Lynch *et al.*, 2004). High fire frequencies under wetter climates suggested that stand type, species composition or fuel accumulation were more important than climate in determining fire occurrence there.

Our data suggest that climatic factors may have been of greater importance at Paradox Lake. Palaeoclimate simulations using a GCM suggest a weaker Aleutian Low in winter and a strengthened Subtropical High in summer during the early Holocene (Bartlein *et al.*, 1998), leading to more ‘continental’ conditions then (increased lightning strikes; Reap, 1991). Conversely, a stronger Aleutian Low and weaker Subtropical High in the later Holocene would have led to wetter conditions with fewer convective storms and lightning ignitions. Thus, when climatic conditions were warmer and driest during the early Holocene, fire event frequencies are also highest. When climatic conditions were cooler and wetter during the late Holocene, fires were less frequent. While fuel loads may be different between *Populus–Salix* and *Picea glauca–Betula* associations (Johnson, 1992), FEF were statistically indistinguishable between these two vegetation types in the fossil record (Table 2), also favouring a climatic explanation.

Different methodologies may also contribute to contrasting fire histories. We used the Paradox Lake charcoal data set to compare our calculations of FEF using CHAPS (threshold ratios) with the methodology of Lynch *et al.* (2003, 2004), which examines the distribution of residual peaks (Clark and Royall, 1996; Clark *et al.*, 1996). We calculated residuals from the charcoal data, using Lowess smoothing filters of 300 and 500 years to match the 300- and 500-yr window widths from CHAPS (Gavin *et al.*, 2003). A sensitivity analysis of residual threshold values and MFI estimates suggests that > 0.15 or 22% of the residual CHAR values (D. Hallett, unpublished data, 2005) identify charcoal peaks as local fires using our known fires and soil charcoal ages. The residual method

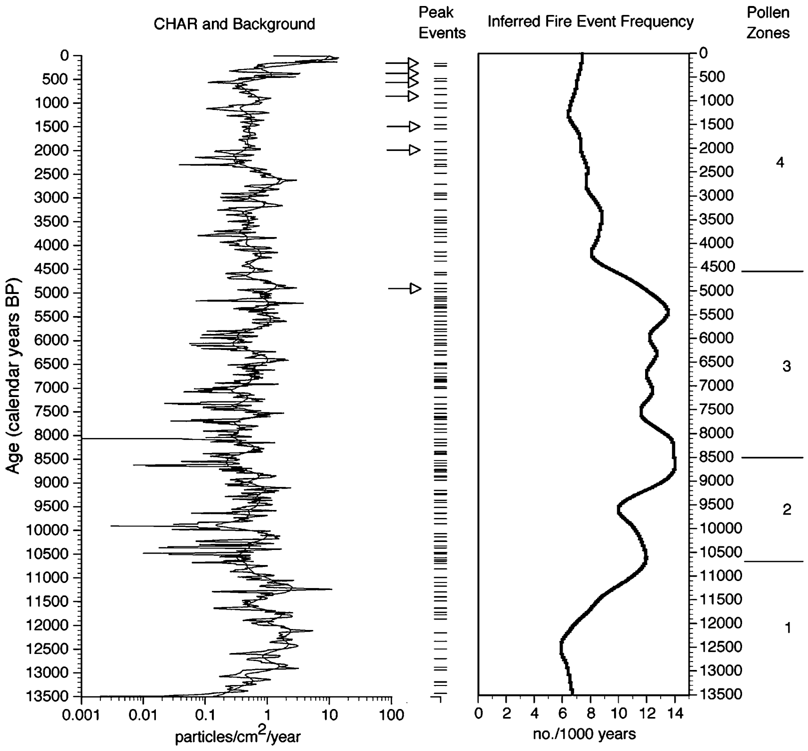

Figure 9 Charcoal accumulation rates (CHAR, particles/cm^2 per yr), peak events, and inferred fire event frequency (no fires/1000 years) for the Paradox Lake, using methodology of Long *et al.* (1998). Arrows show where soil charcoal ages represent maximum ages for locally calibrated CHAR peaks. Pollen zones are shown for reference to vegetation reconstructions

Table 4 Fire interval summary statistics using residual analysis (300 Lowess smoothing and 0.15 threshold value), and tests for significant difference between periods by Kolomogorov–Smirnov 2-sample tests

Age interval (yr BP)	Fire intervals			Kolomogorov–Smirnov 2-sample tests (yr BP)[a]			
	N	mean ± s.d.	(Range yr)	−48–4600	4600–8500	8500–10700	10700–13500
−48–4600	32	142 ± 70	(20–270)	–	$p < 0.05$	$p < 0.01$	NS
4600–8500	41	93 ± 61	(20–290)	$p < 0.05$	–	NS	$p < 0.05$
8500–10 700	27	86 ± 67	(30–350)	$p < 0.01$	NS	–	$p < 0.05$
10 700–13 500	24	115 ± 52	(40–240)	NS	$p < 0.05$	$p < 0.05$	–
all −48–13 500	124	108 ± 67	(20–350)				

[a] Table entries are KS 2-sample tests with no difference being NS where $p > 0.05$ and significant differences in fire interval data are shown at the $p < 0.05$ or 0.01 level.

produces similar results to our selected CHAPS scenario, by showing more frequent fire in Zones 2 and 3, and less frequent fire in Zones 1 and 4 and similar MFI estimates for the Holocene (Table 4). We conclude that methodological differences do not alter the general results of FEF reconstructions for the Paradox Lake CHAR series.

Conclusions

Despite the importance of ecosystem processes such as fire, the long-term relationships between disturbance, climate and vegetation type are incompletely understood (Lynch *et al.*, 2003). Palaeoecology can assist in establishing relationships between these variables in the Boreal forest (ie, Clark and Royall, 1996; Clark *et al.*, 1996; Carcaillet and Richard, 2000; Carcaillet *et al.*, 2001). The record from Paradox Lake, the longest and most detailed record of fire and vegetation in Alaska, is an important demonstration of the inextricable linkage between climate, vegetation and fire. FEFs are lowest when shrub and herb tundra grew around the lake. FEFs increased with the immigration of *Salix*, *Populus*, *Betula* and *Picea glauca*. FEFs declined with the immigration of *Alnus* and *Picea mariana*.

Today, fire frequencies within *P. mariana* forests are typically greater than for uplands of *P. glauca* (eg, Yarie, 1981; Larsen, 1997). Yet our reconstructions suggest that fire burned more often in *P. glauca*-dominated forests than when *P. mariana* was more common around the lake. We believe this is due to two factors. First, the early Holocene forests of *P. glauca* and *Betula* existed during summers that were longer and drier than today. The combination of increased flammable coniferous biomass in the uplands and continuation of relatively warm summers must have allowed for periodically drier forest fuels. Lightning ignitions may have been more common during the early Holocene because of drier continental climate. Today, lightning storms are rare on the Kenai Peninsula, and ignition sources are dominated by human activity (Gabriel and Tande, 1983; De Volder 1999). Second, the increasingly wetter and cooler climate of the late Holocene was probably important. Even though *P. mariana* grows widely within the Kenai lowlands, its distribution within the Paradox Lake drainage basin is limited to a narrow boggy band immediately around the lake. Thus, *P. mariana*'s impact on the spatially aggregated fire event frequency of the drainage basin must be small.

Determination of fire event frequencies during the late Holocene using multiple proxies produced remarkably consistent results. For example, De Volder's (1999) stand-age and burn pole analysis documented recent fire return intervals up to 185 years in black spruce; Berg and Anderson's (2006) late Holocene soil charcoal fire return intervals for Paradox Lake average 190 years; Lynch *et al.*'s (2003) analysis of sedimentary charcoal in Rock Lake suggests a fire return interval of 194 years; and Lynch *et al.* (2004) suggests return intervals of < 230 years. These figures compare with our fire return intervals of up to 195 years (Table 2).

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