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A 1000-year record of forest fire, drought and lake-level change in southeastern British Columbia, Canada

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Abstract: High-resolution charcoal analysis of lake sediments and stand-age information were used to reconstruct a 1000-year fire history around Dog Lake, which is located in the montane spruce zone of southeastern British Columbia. Macroscopic charcoal (>125 μm) accumulation rates (CHAR) from lake sediment were compared with a modern stand-origin map and fire-scar dates in the Kootenay Valley to determine the relative area and proximity of fires recorded as CHAR peaks. Small fires close to the lake and larger more distant fires appear as similar-sized peaks in the record. This information reinforces previous findings where CHAR peaks represent a complex spatial aggregation of local to extra-local fires around a lake site. CHAR peaks indicate frequent stand-destroying fires during the 'Mediaeval Warm Period' (~AD 1000–1300), and other significant fires at *c.* 1360, 1500, 1610 and 1800. We also present a proxy measure of lake-level changes based on a comparison of accumulation rates of *Chara globularis*-type oospores over the last millennium and the present distribution of charophytes in the lake basin. Lower water levels, represented by few or no *Chara* oospores, correspond to times of regional drought and large forest fires around the lake. Higher lake levels, represented by increased *Chara* oospore accumulation rates, correspond to wetter climate periods during the Oort, Wolf, Spörer and Maunder solar sunspot minima, when little or no fire activity occurs around the lake.

Key words: Macroscopic charcoal analysis, fire history, lake sediments, solar forcing, lake-level variations, charophyte, British Columbia, Canada, late Holocene.

Introduction

Fire is an important disturbance process that influences the structure, composition and distribution of vegetation over time (Agee, 1993; Johnson, 1992). Most estimates of prehistoric fire frequency in the Canadian Rocky Mountains are based on dendrochronological records that extend over the last 500 years (Johnson and Larsen, 1991; Masters, 1990; Rogeau, 1996; Tande, 1979). These records are useful for creating time-since-fire or stand-origin maps that show a complex pattern of overlapping past fires on a given landscape. Determining the temporal and spatial variability of fire regimes from stand-origin maps is limited by the age of trees and by the erasure effect, where recent fires burn over and remove evidence of past fires on the landscape (Johnson and Gutsell, 1994). In order to increase our understanding of the temporal and spatial variability of fire regimes, we need to link high-resolution dendrochronological data with long-term macroscopic charcoal records from continuous lake sediments (Lertzman *et al.*, 1998). The greater temporal depth of charcoal records allows assessment of fire frequency over long periods of variable climate (e.g., Clark, 1988a).

Macroscopic charcoal >50 μm represents a local signal of fire in lake-sediment records (Clark, 1988b). Charcoal analysis methods involving contiguous sampling and wet-sieving for charcoal >125 μm are now used widely to reconstruct fire-history records over millennial timescales (Carcaillet *et al.*, 2001; Hallett and Walker, 2000; Long *et al.*, 1998; Millspaugh and Whitlock, 1995; Millspaugh *et al.*, 2000; Mohr *et al.*, 2000). Charcoal accumulation rates (CHAR) provide a continuous time series of slowly varying background charcoal related to erosion, secondary transport or remobilization of charcoal in a watershed, and highly varying prominent peaks that represent airborne deposition by fire events close to the lake. Each lake site has a unique charcoal source area based on its watershed size, forest cover and topography. Charcoal peaks can occur in the sediments of unburnt watersheds downwind from a fire, or peaks may be a result of

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redeposition of charcoal from the littoral to the profundal zone (Whitlock *et al.*, 1997; Whitlock and Millspaugh, 1996). Taphonomic concerns for distribution of lake-sediment charcoal make independent proof of fire around a site necessary before charcoal peaks can be confidently described as a fire event. Information such as stand ages, fire scars, recent fire records (e.g., Clark, 1990; Gardner and Whitlock, 2001; Hallett and Walker, 2000; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995; Tinner *et al.*, 1998) and even radiocarbon dated soil charcoal remains (Gavin, 2000; Hallett, 2001) provide local evidence of fire that can be compared to timing of CHAR peaks. Combining all or some of these fire-history techniques in one study is the best tool for calibrating CHAR records to historic fire events and using this calibration as a basis for reconstructing fire regimes over millennial timescales.

Hallett and Walker (2000) analysed a 10 000-year CHAR record from Dog Lake in the Kootenay Valley to better understand the role of fire during the Holocene. This study defined a range of natural variability for fire frequency and vegetation change over millennial timescales in the southern Canadian Rockies (Hallett and Walker, 2000). Modern fire frequencies, with ~230 year mean-fire-return intervals, were shown to be established in the last 4000 years, coeval with the onset of cool and moist Neoglacial climate in the region (Luckman *et al.*, 1993; Ryder and Thompson, 1986). During the last 2000 years, a small increase in fire frequency, along with the reoccurrence of dry-open forest types inferred from pollen ratios, occurred around Dog Lake. The most recent shift in fire frequency and pollen-inferred vegetation change agree with the timing of the 'Mediaeval Warm Period' (MWP) and 'Little Ice Age' (LIA) climate periods. In order to test this result, we analysed charcoal with decade-scale resolution over the last millennium. More recent fire-history information in Kootenay National Park (KNP) shows that fire frequency after *c.* 1788 and *c.* 1928 decreased, probably due to cool LIA climate and increased precipitation in the twentieth century (Masters, 1990). Neither fire suppression since *c.* 1919 nor the construction of the Windermere highway through the park have changed fire frequency from pre-European times. Most of the area burned in KNP is the result of large, high-intensity, infrequent, stand-replacing fires (Masters, 1990) that are associated with blocking high-pressure circulation anomalies and peak lightning activity in July and August (Johnson and Wowchuk, 1993; Nash and Johnson, 1996). Small, low-intensity, surface fires occur more frequently but do not spread across large areas.

Our goal is to compare closely the modern dendrochronological fire-history record with high-resolution CHAR peaks, and reconstruct a detailed fire history around Dog Lake for the past 1000 years. Knowledge of fire-frequency variations over long time periods and changes in climate are considered essential information for park managers who are mandated to preserve the integrity of ecosystem processes such as fire. Management decisions, such as fire suppression and prescribed burning, need to be supported by science because they can impact on the natural variability of fire regimes. Most importantly, understanding when large fires have occurred, and will potentially occur in the future, are necessary for public-safety and resource-management decisions in protected areas. KNP is now mandated to restore 50% of long-term, average fire cycles. As in any restorative activity, managers need the best available estimate of what is to be restored, and this can be defined using long-term palaeoecological records.

In this paper, we also present a record of *Chara globularis*-type oospore accumulation rates in Dog Lake sediments, which may infer past lake-level changes. *Chara* oospore macrofossils are common in calcareous lakes in British Columbia and can be identified to genus and species level (Haas, 1994; Mann *et al.*, 1999; Wood, 1967). Most genera and species have partly known ecological requirements for optimal growth such as pH, water depth, temperature and clarity, and nutrient regimes. Changes in these conditions can impact charophyte growth in lakes if sensitive taxa are present. Changes in charophyte distribution or abundance within an assemblage may be used to infer past conditions in a lake (Haas, 1994; 1999). Understanding the current distribution of growth and species composition in a basin provides a key to interpreting fossil-assemblage changes through time. Multilake studies of regional and continental-scale lake-level changes over the Holocene have provided information on atmospheric circulation patterns linked to changes in climate (Harrison and Metcalfe, 1985). Here we interpret a 1000-year high-resolution record of *Chara* oospore macrofossil remains based on modern distribution patterns and propose an atmospheric-based mechanism for lake-level variability at this site.

Modern setting and study site

The north–south trending Kootenay Valley sits just west of the Continental Divide in southeastern British Columbia (Figure 1). Dog Lake (50° 46′N, 116° 06′W, elevation 1183 m, 15.1 ha) is located 3 km east of the Kootenay River in Kootenay National Park within the Montane Spruce (MS) forest zone (Meidinger and Pojar, 1991). Dog Lake has a flat rectangular basin with steep east and west sides, and an extensive littoral zone at the north and south ends (Figure 1). The lake is alkaline (pH = 8.3) (Donald and Alger, 1984) with abundant charophyte mats growing in and around the deepest section (4–4.7 m) of the basin. The calcium carbonate crust that forms around charophytes during yearly growth eventually decays and helps to form laminations in cal-

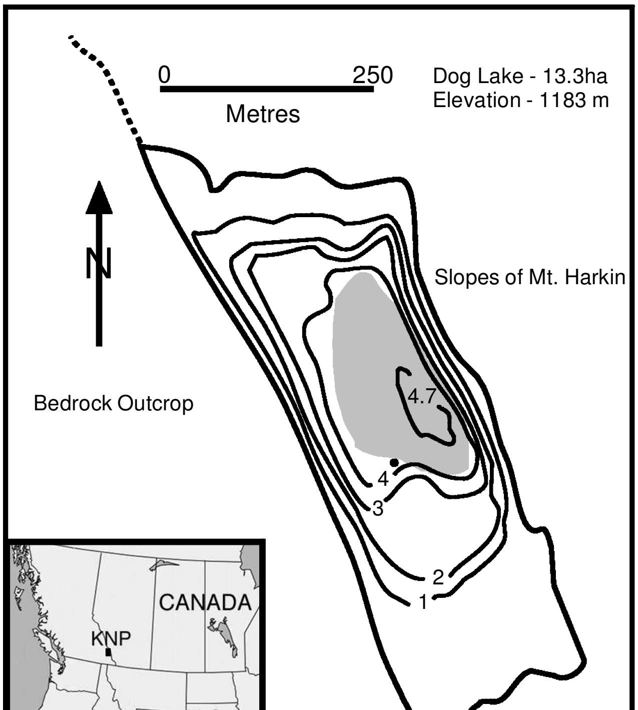

Figure 1 Bathymetric map of Dog Lake with a dot showing the 4 m coring location used in this study. The extent of current charophyte growth is presented as a shaded area in the deeper portions of the lake. The coring location for Hallett and Walker (2000) was located at the deepest 4.7 m portion of the basin. Inset is a map of western North America showing the location of Kootenay National Park (KNP) in southeastern British Columbia.

careous gyttja. Watershed area is 2080 ha with an inlet to the lake entering from a wetland system to the southwest and a small outlet at the northwest end drains into the Kootenay River. The inlets and outlets for the lake are small and most active during spring snowmelt in this mountainous environment. Water levels fluctuate by 0.5 m annually with the highest levels in late spring while snowpacks are melting, and low levels occur in late summer and autumn. Freeze-up for this dimictic lake occurs in early November and ice breakup occurs in early May (Donald and Alger, 1984).

Mixed stands of *Pinus contorta*, *Pseudotsuga menziesii* and *Picea glauca* grow on the slopes of Mt Harkin east of the lake and on a bedrock outcrop to the west, which separates the lake from the Kootenay River. Immediately around the lake, mixed stands of *Pinus contorta* and *Pseudotsuga menziesii* grow on xeric sites, with *Picea glauca*, *Populus tremuloides* and *Betula papyrifera* found on mesic sites. At subalpine elevations upslope from the lake, the Englemann Spruce-Subalpine Fir zone (ESSF) dominates with closed stands of *Picea engelmannii* and *Abies lasiocarpa.* The drier Columbia Valley lies just west of the Kootenay Valley and has forest classified as Interior Douglas-fir zone (IDF) (Meidinger and Pojar, 1991). A ratio of dry/wet pollen types and macroscopic charcoal data for the Holocene (Hallett and Walker, 2000) show how dry climate and disturbances such as fire can create conditions that allow IDF forest to periodically increase its distribution in the upper parts of the Kootenay Valley. IDF vegetation currently exists in the Kootenay Valley at lower elevations in the south (~900 m) near Canal Flats, where the Columbia and Kootenay valleys converge.

Modern climate in southern British Columbia is strongly influenced by the semi-permanent 'centres of action' over the north Pacific Ocean called the Aleutian Low and the eastern subtropical Pacific High. Moist westerly onshore flow originating from the Aleutian Low delivers precipitation in the form of snow during the winter months and rain in warmer seasons. Cold Arctic air may penetrate west of the continental divide into the southern Canadian Rockies and create cold dry conditions for portions of the winter. Dry summer climate results from the dominance of the blocking Pacific High (Lydolph, 1985) and can lead to drought and forest fires in the region if a strong blocking ridge of high pressure remains stationary for long periods (Skinner *et al.*, 1999; 2002). Seasonal high summer temperatures and drought create the conditions for extreme fire weather in the Canadian Rocky Mountains, which is strongly associated with mid-tropospheric anomalies at 50 KPa height levels (Johnson and Wowchuk, 1993). Persistent ridges of high pressure block moisture from coastal air masses by redirecting mid-latitude storm tracks, and create the conditions that can lead to dry fuels, convection, dry lightning storms and high winds (Bessie and Johnson, 1995; Nash and Johnson, 1996; Rorig and Ferguson, 1999). A combination of these variables may cause large stand-destroying fires. There is evidence suggesting that high-pressure circulation and blocking ridges at 50° N may be larger and/or more persistent during active phases of the 11-year solar cycle (Haigh, 1996; Shindell *et al.*, 1999; 2001). In the past four decades, fire years with large area burned in North America are associated with the peaks or maxima of 11-year solar irradiance cycles (Auclair, 1992; Auclair and Carter, 1993). A response of climate (and fire) to solar forcing at century scales can be tested by comparing the timing of fires to atmospheric $\Delta^{14}C$ residual data, which is a proxy measure of solar activity and climate (Stuiver and Braziunas, 1989; 1993; Stuiver *et al.*, 1997; 1998).

Field and laboratory methods

In August of 1998, we retrieved a 60 cm core from Dog Lake using a 7.5 cm diameter clear lexan tube fitted with a one-way valve and operated with a rigid drive rod. The coring procedure recovered the mud–water interface intact from 4 m of water, approximately 2 m outside the current growth zone of *Chara globularis* (Figure 1). Our primary goal was to retrieve an undisturbed short core used for constructing a high-resolution macroscopic charcoal record over ~1000 years. However, collecting the core outside the current charophyte zone allowed us to assess the range of past charophyte growth, since the distribution of macroremains in a flat-bottomed lake reflects primarily local vegetation distribution (Vance and Mathewes, 1994). In the laboratory, we sampled this core contiguously in 0.5 cm increments with a close-interval sectioning device (Glew, 1988) and placed 10 cm^3 subsamples in plastic vials. Magnetic susceptibility measurements were done on each sample depth using a Sapphire meter at the University of Oregon. Magnetic susceptibility measurements are used to detect allochthonous minerogenic input resulting from erosion after a fire or flood event, or deposition of a volcanic tephra (Thompson and Oldfield, 1986).

Sediment subsamples were soaked in 10% HCl for 24 hours to remove carbonates. The treated 10 cm^3 sediment samples were then gently washed through a 125 μm sieve and residues were placed in a gridded petri-dish. Each sample residue was tallied for macroscopic charcoal and *Chara globularis* oospores using a dissecting microscope at ×400 magnification. Charcoal fragments >50 μm are evidence of local fire events in lake sediments (Clark, 1988b; Clark *et al.*, 1998), but we counted a >125 μm sieve fraction of charcoal because it is more practical to count (Millspaugh and Whitlock, 1995). The concentration values for both macroscopic charcoal and *Chara* oospores were divided by deposition time (yr cm^{-1}) to calculate a total charcoal particle accumulation rate (particles cm^{-2} yr^{-1}) or CHAR (Long *et al.*, 1998; Millspaugh and Whitlock, 1995), and a total *Chara* oospore accumulation rate (*Chara* oospores • cm^{-2} • $year^{-1}$). We used the charcoal decomposition methods of Long *et al.* (1998) to determine the peak event dates for our CHAR record. A peak event is defined when CHAR values exceed the background component of the data (determined by a 50-year locally weighted moving average) by a threshold ratio of 1.1.

Results and interpretations

Chronology

The 60 cm sediment core consisted of laminated calcareous gyttja. The sediment age-versus-depth relations for the core are based on an accelerator mass spectrometry (AMS) ^{14}C date at the base and a thin Mt St Helens We tephra layer located near the middle of the core (Hallett *et al.*, 2001). Tree-ring data from around the lake indicated that the last stand-destroying fire was at *c.* 1800 (Masters, 1990). We plotted a simple linear interpolation of the radiocarbon and tephra age data and found that a large CHAR peak at 12 cm corresponded to this fire. The stand-age date at *c.* 1800 suggests the fire occurred at *c.* 1790 because there is a slight lag in stand initiation after disturbance (Johnson and Gutsell, 1994). We used this information to mark the top of the charcoal peak at *c.* 1800 in our age model; however, the initial part of the peak begins at *c.* 1790 when the actual fire event occurred. A second AMS ^{14}C date on a needle collected at 24 cm was not used directly because its calibrated age is slightly older than the more precisely dated Mt St Helens We tephra layer (Yamaguchi, 1983; 1985) located 1.5 cm below. However, a simple linear interpolation crosses within the lower two-standard deviation calibrated age range of the rejected AMS ^{14}C date. Linear interpolation between the calibrated ages was used to calculate sediment deposition time (Figure 2). High-resolution 0.5 cm sampling of the core resulted in average sampling intervals of 7.3 years per sample between 60 and 26.5 cm, 10.9 years between 26.5 and

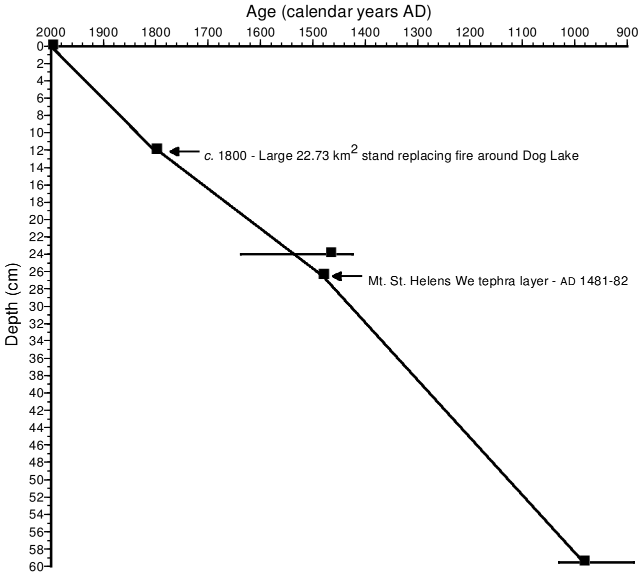

Figure 2 The age-versus-depth model for Dog Lake surface core with filled squares representing AMS dates on conifer needles and their error range defined at two standard deviations. The location of the Mt St Helens We tephra layer (AD 1481–82) (Hallett *et al.*, 2001; Yamaguchi, 1983; 1985) is indicated by an arrow and used to construct a simple linear age model along with the basal AMS age.

12 cm, and 8.3 years between 12 cm and the top of the core. Uncalibrated radiocarbon dates (^{14}C yr BP) and calibrated ages (cal. yr AD) are listed in Table 1.

Time-since-fire map, CHAR and magnetic susceptibility

The time-since-fire or stand-origin map for the lower Kootenay Valley (Figure 3) was constructed using dendrochronologic data from Masters (1990) along with additional fire-scar and stand-age data obtained by the Kootenay National Park warden service (R.C. Walker, unpublished data). The time-since-fire map presents the dates and spatial extent of the most recent fires around the lake. Stand-age data do not precisely date a fire event because the establishment and growth of trees after a stand-destroying fire require several years to establish (Johnson and Gutsell, 1994). Furthermore, estimating tree ages from increment cores may be confounded by sampling techniques (Wong and Lertzman, 2001). Fire-scar dates are presented on the map to confirm the time-since-fire estimates from stand ages or to provide evidence of smaller, more localized, surface fires within an even-aged stand. The spatial and temporal information of fires becomes less precise for older events because they are recorded by only a few individuals in the oldest age classes (Johnson and Gutsell, 1994). The time-since-fire map suffers from an erasure effect where past stand-age information and fire evidence are burned over (or consumed) by more recent fires.

The 1000-year CHAR record compares favourably with a summary of fire-scar and stand-origin dates for the Kootenay Valley. Even with subdecadal sampling intervals, there was considerable autocorrelation due to lag times associated with charcoal deposition after a fire (Whitlock *et al.*, 1997; Whitlock and Millspaugh, 1996). Many CHAR peaks extended over a ~40-year period although some peaks, such as at *c.* 1800, appear sharp and distinct (Figure 4). With decadal resolution, the annual fire-scar information becomes less useful for our comparison because numerous fire scars in the 1800s–1900s match broad CHAR peaks and some scars match no peaks. Fire scars in the 1700s have no CHAR equivalent, but a fire scar at *c.* 1438 outside the watershed appears to match a small CHAR peak. The stand-age fire dates within the watershed appear to match the first four CHAR peaks. This suggests that stand-replacing fires are best reflected in the CHAR record. Stand ages located outside the watershed are shown at *c.* 1648, 1720, 1828, 1851, 1868 and 1893, and these distant fires do not have distinct peaks in the CHAR record. The best matches are with historic watershed fires at *c.* 1800, 1917, 1956 and 1980, which are marked by arrows in Figure 4. Peak event (fire) dates allow us to calculate a mean fire interval (MFI) of 46 ± 5 years (mean ± standard error) for all fires recorded by the lake sediments over the last 1000 years. The MFI from AD 1000 to 1300 ('Mediaeval Warm Period') is 37 ± 7 years and the MFI from AD 1350 to 1850 ('Little Ice Age') is 62 ± 8 years. Not all of the peak (fire) events can be calibrated as local stand-destroying fires so the MFI calculations are at best an overestimate of fire activity in the valley.

The large stand-destroying at *c.* 1800 fire created a CHAR peak of 2.7 particles $cm^{-2} yr^{-1}$ and probably occurred between AD 1790 and 1800. There is CHAR evidence corresponding to a large *c.* 1917 fire south of the lake, a small *c.* 1956 fire to the south, and finally from a small *c.* 1980 fire occurring on the east shore of the lake. Stand-origin and fire-scar dates from the *c.* 1720 fire were not recorded in the lake, which is not surprising considering the fire occurred on the far west side of the valley outside the lake watershed. In general, fires occurring outside the watershed are not well recorded by the Dog Lake CHAR record (Figure 4). The oldest stand-age fire date at *c.* 1648 could be considered a match for a CHAR peak extending from *c.* 1610 to 1640, but this small remnant stand also resides outside the watershed. The size of the CHAR peak suggests that the *c.* 1648 fire or an earlier event at *c.* 1610 may have burned stands closer to the lake, but the erasure effect of more recent fires has removed any landscape-level evidence of this past disturbance.

As expected from empirical studies (Clark *et al.*, 1998; Gardner and Whitlock, 2001), the size of CHAR peaks tends to decrease with fires located farther from the lake (Figure 5). Fires occurring next to the lake at *c.* 1980 and *c.* 1800 produced a range of CHAR values from 0.2–2.7 particles $cm^{-2} yr^{-1}$ and seem to represent the area of each fire. The *c.* 1808–1820 fires cannot be resolved from the *c.* 1800 CHAR peak. The *c.* 1956 and *c.* 1917 fires have similar CHAR values and are located >2 km from the lake, but have

Table 1 Uncalibrated radiocarbon, calibrated ages, volcanic and tree-ring based ages for Dog Lake

Depth (cm)	Uncalibrated ^{14}C age (^{14}C yr BP)	$\delta\ ^{13}C$	Calibrated age (cal. BP)[a]	Calibrated age (cal. AD)[a]	Material dated	Lab. number	Reference
12				AD 1800	Tree-ring count, stand-age determination and fire scars		Masters (1990)
26.5				AD 1481–82	Tree-ring count for Mt St Helens We tephra		Yamaguchi (1983; 1985)
24	400 ± 50	–25.00	526 (482) 313	1424 (1468) 1637	Conifer needle	CAMS 57053	
59.5	1070 ± 50	–24.07	1063 (966) 920	887 (984) 1030	Conifer needle	CAMS 53971	

[a]Age ranges are presented as the median intercept with its two-sigma error range (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998)

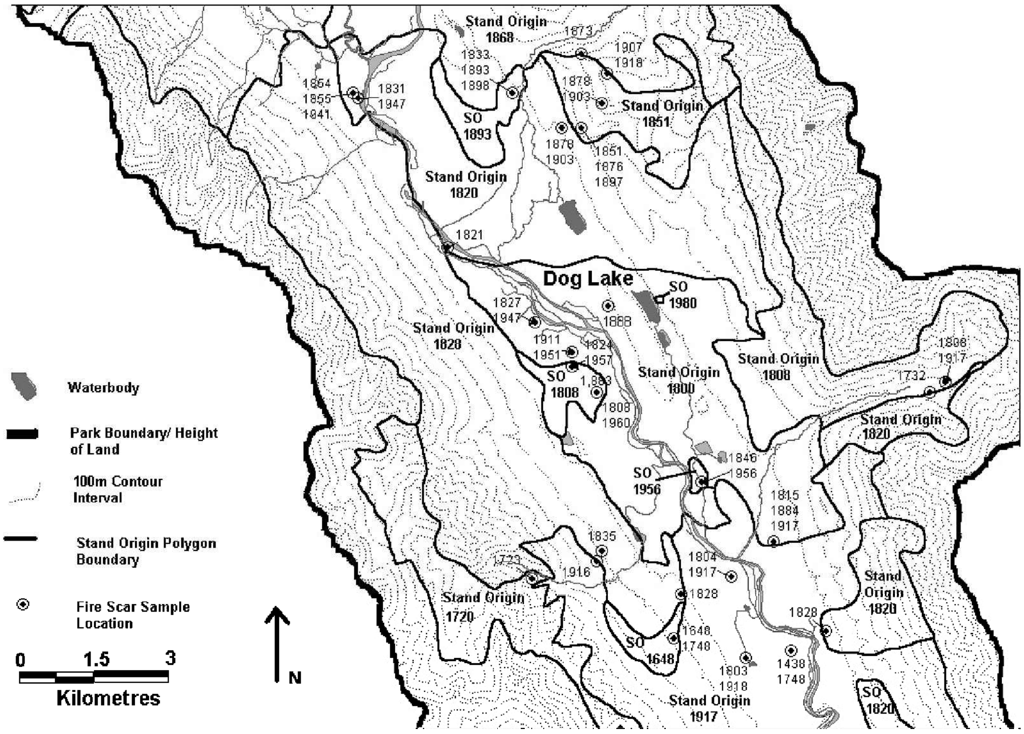

Figure 3 The time-since-fire map for the Kootenay Valley around Dog Lake. Stand-origin (SO) polygons are labelled with the date of the even-aged stand and the associated fire event. Fire-scar locations throughout the valley are labelled with double circles beside their respective fire date. The *c.* 1800 stand-origin polygon represents the largest historical stand-replacing fire around the lake recorded by Masters (1990).

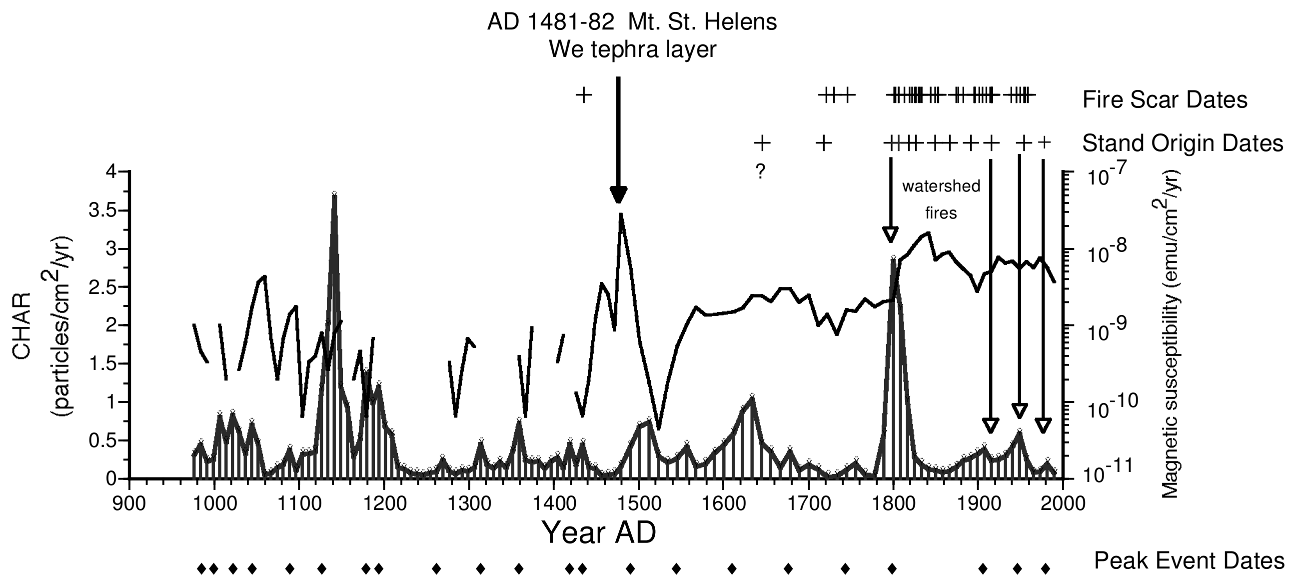

Figure 4 Plot of charcoal accumulation rates (CHAR) and magnetic susceptibility accumulation rates for the Dog Lake surface core. Fire-scar dates and stand-origin dates from Figure 3 are summarized at the top right in relation to the time axis. Stand-origin dates located in the watershed are marked with arrows. The magnetic susceptibility peak that signifies the Mt St Helens We tephra layer is indicated by an arrow (Hallett *et al.*, 2001). Peak event (fire) dates determined by charcoal decomposition methods (Long *et al.*, 1998) are presented below the time axis.

dramatically different area burned. The large 60 km^2 *c.* 1917 fire was recorded as 0.4 particles cm^{-2} yr^{-1}, but appears similar to a smaller fire signal because of its 5 km distance from the lake. This suggests the charcoal source area for Dog Lake may be up to 5 km if strong winds carried charcoal from the edge of the *c.* 1917 fire. However, a local fire is most likely within 2 km of a lake site based on empirical studies of charcoal deposition (Clark *et al.*, 1998; Gardner and Whitlock, 2001; Ohlson and Tryterud, 2000) and comparison of historic fire records around a lake (Tinner *et al.*, 1998). The last CHAR peak corresponding to the *c.* 1648 fire may have been larger in area and/or closer to the lake based on its 1.1 particles cm^{-2} yr^{-1} CHAR value. The erasure of past fire evidence by more recent events limits our knowledge of fire size and its proximity to the lake. Most fires recorded as CHAR peaks in Dog Lake occurred to the south, which is in agreement with the measured direction and distribution of summer wind in the Kootenay Valley (R.C. Walker, unpublished data).

The magnetic susceptibility and CHAR records are not correlated statistically ($r = -0.07$) over the last 1000 years, although an increase in magnetic susceptibility after the *c.* 1800 fire may indicate increased erosion following a stand-destroying fire around the lake (Millspaugh and Whitlock, 1995; Thompson and Oldfield, 1986). A large magnetic susceptibility peak at 26.5 cm marks the location of the AD 1481–82 Mt St Helens We tephra

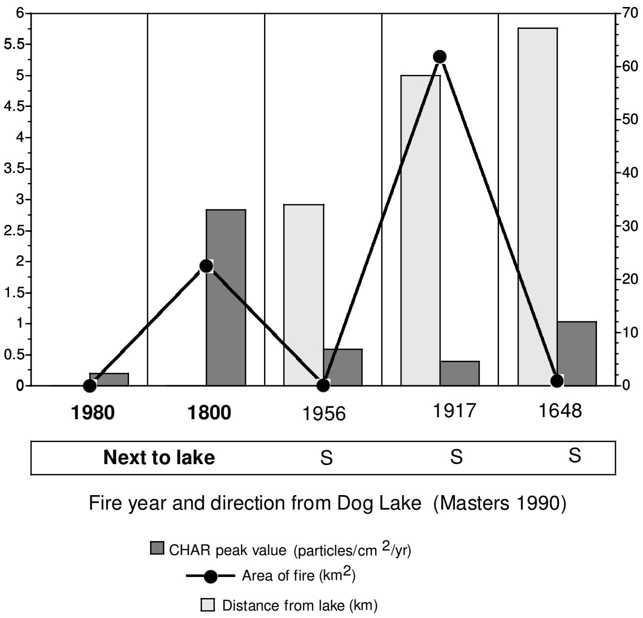

Figure 5 Combination plot showing CHAR peaks that correspond to known fire dates from Figure 3. CHAR peak values are plotted along with their distance from the lake and the area of the fire, which is calculated from the stand-age map in Figure 3. CHAR peaks are presented from left to right with increasing distance from the lake site.

layer and has been confirmed with microprobe analysis (Hallett *et al.*, 2001). Magnetic susceptibility is low and displays gaps with measurements of zero between *c.* 1200 and *c.* 1440 and only a few peaks are noted in this interval. There are consistently high values from *c.* 1540 to present.

Dog Lake CHAR and the atmospheric $\Delta^{14}C$ residual data (Stuiver *et al.*, 1998) show no significant correlation ($r = -0.10$ $p < 0.15$) over the last 1000 years, but the timing of some fires seems to correspond visually to active solar periods on century scales (Figure 6). Improving the chronology of the CHAR data may improve correlation results especially if annual laminations were present in the core. In the Kootenay Valley, large fires at *c.* 1800 and inferred large fires at *c.* 1610–1648, *c.* 1180, *c.* 1120 and *c.* 1020 correspond with century-scale negative ^{14}C anomalies and active sun. Conversely, there is little evidence of fire during quiet solar periods such as the Maunder Minimum and the early portion of the Spörer solar (sunspot) minimum.

Spectral analysis of CHAR

We used harmonic analysis to determine if the CHAR time series displays any dominant periodicities in the last 1000 years. Spectral results of the raw time series were analysed using SPECTRUM (Schulz and Stattegger, 1997) which allows for data that is unevenly sampled such as CHAR (Figure 7). This program avoids interpolation techniques that can introduce red noise into spectral results. There were significant periods found at ~160 and 210 years (Siegel, 1980). Similar solar modulated 206-year and 148-year periods are found in the spectral results of atmospheric $\Delta^{14}C$ residual data (Sonnett and Finney, 1990; Stuiver and Braziunas, 1993) and a ~206-year period also exists in the solar modulated ^{10}Be record (Beer *et al.*, 1988). The ~206-year periodicity dominates the character of the atmospheric $\Delta^{14}C$ residual data through the Wolf, Spörer and Maunder oscillations over the last 1000 years (Stuiver and Braziunas, 1989; 1993; Stuiver and Quay, 1980). Other palaeoenvironmental records in North America also display evidence of solar modulated periodicities over the last two millennia (Hodell *et al.*, 2001; Laird *et al.*, 1996; Sonnett and Suess, 1984; Stuiver *et al.*, 1997; Yu and Ito, 1999).

Charophyte macrofossils and inferred lake-level change

In Dog Lake, we found only *Chara globularis*-type oospores in the last 1000 years of sedimentation with no change in species over time. *Chara* oospore accumulation rates at this coring site varied considerably over the last 1000 years and may indicate distribution shifts in local charophyte abundance. The charophyte record and atmospheric $\Delta^{14}C$ residual data are not correlated ($r = 0.07$, $p < 0.15$); however, CHAR and *Chara* oospore accumulation rates are weakly, but significantly, correlated ($r = -0.23$, $p < 0.01$) over the last 1000 years. The negative relationship suggests that fire events correspond with low charophyte productivity. The occurrence of forest fire (and low charophyte productivity) supports an interpretation of dry climate and possibly lower lake levels.

Expansion and contraction of charophyte beds in the basin may be used to infer long-term changes in lake level. In Dog Lake, dense charophyte growth exists at water depths of ~4 m or more with no growth in the shallower areas of the basin (Figure 1). The sediment core was collected 2 m outside the current growth area of charophytes. We assume that low *Chara* oospore accumulation rates represent times of poor production over the core site. If water levels increase, then the charophyte beds should be able to expand in the flat basin and oospore production should increase over the core site. In the last decade of sedimentation, low oospore accumulation rates (0.1 oospores cm^{-2} yr^{-1}) correspond with absence of local charophyte growth indicating that the lake may be experiencing a relatively low water stage from *c.* 1980 to present. Air-photo analysis shows that in 1952 and 1958 the lake area was 15.9 ha, in 1978 the area was 12.7 ha and in 1995 the area was 13.3 ha, which suggests a lowering of lake levels from 1950 to present. The decrease in *Chara* oospores from the 1950s to 1998 corresponds with this historical analysis (Figure 6).

High oospore values ranging from 0.2 to 1.5 oospores cm^{-2} yr^{-1} indicate increased charophyte growth and may represent higher water levels for AD 1820–1870, 1690–1760, 1520–1550, 1390–1420, 1300–1360, 1020–1100 and 980 (Figure 6). High-inferred lake levels seem to occur during quiet solar periods, such as the Oort, Wolf, Spörer and Maunder solar (sunspot) minima, when compared to the atmospheric $\Delta^{14}C$ residual data. Low oospore values ranging from 0.0 to 0.1 oospores cm^{-2} yr^{-1} indicate little or no charophyte growth over the coring site and infer low water levels for AD 1120–1300, 1460–1500, 1560–1680, 1780–1820, 1880–1940 and 1980 to present. Prolonged intervals with low inferred lake levels correspond well with active solar periods, such as during the Grand Solar Maximum (AD 1100–1250), when compared to the atmospheric $\Delta^{14}C$ residual data (Figure 6).

Discussion

CHAR studies and local fire-history records

This study adds to a body of literature discussing the relationship between macroscopic charcoal deposited in varved, laminated and non-laminated sediments, and known fire events. Comparing macroscopic charcoal preserved in varved and laminated sediments with dendrochronological data, such as stand ages and fire scars, was pioneered in the mixed conifer hardwoods of Minnesota (Clark, 1988a; 1988b; 1990; 1993). Similar methods of comparison have now been used in other parts of eastern North America (Clark and Royall, 1996), the boreal forests of northern Alberta (Larsen and MacDonald, 1998; MacDonald *et al.*, 1991), British Columbia (Hallett and Walker, 2000) and Quebec (Carcaillet *et al.*, 2001), and in Europe (e.g., Tinner *et al.*, 1998). Studies using non-laminated sediments have successfully matched CHAR peaks with known fire events in Oregon (Gardner and

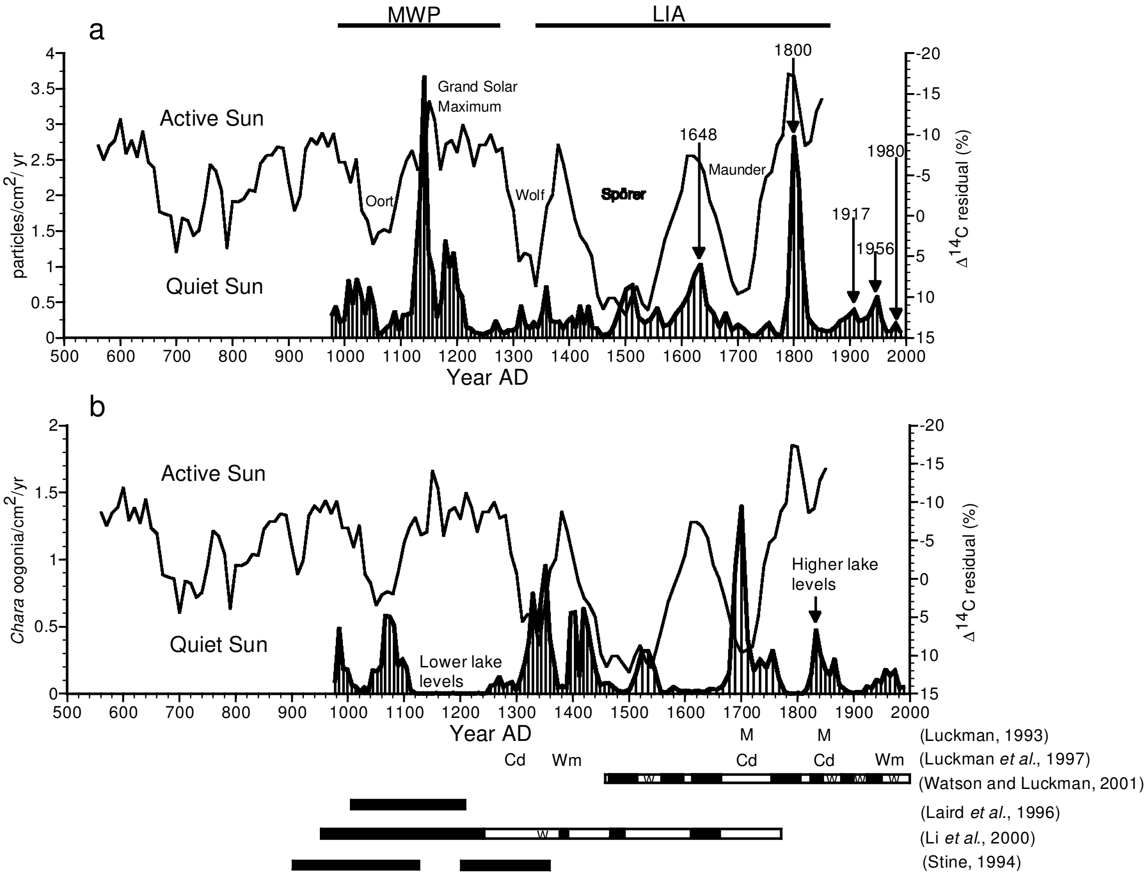

Figure 6 (a) Dog Lake CHAR and the atmospheric $\Delta^{14}C$ residual record (a proxy for solar activity) for the last 1500 years (Stuiver *et al.*, 1998). Arrows indicate fires or peak events, which correspond to stand-origin dates. Century-scale radiocarbon anomalies representing solar (sunspot) minima are labelled along with the Grand Solar Maximum. 'Mediaeval Warm Period' (MWP) and 'Little Ice Age' (LIA) climate periods are identified above the plots. (b) Accumulation rates for *Chara* oospores in Dog Lake and the $\Delta^{14}C$ solar proxy record. High lake levels are inferred by peaks or high values of *Chara* oospore accumulation, while low lake levels are inferred by few or no *Chara* oospores in the sediments. Solid bars below the Dog Lake plots show dry periods in the last 1000 years at other study sites in the Canadian Rockies (Luckman, 1993; Luckman *et al.*, 1997; Watson and Luckman, 2001), the Northern Great Plains (Laird *et al.*, 1996) and the Sierra Nevada (Li *et al.*, 2000; Stine, 1994). Open bars mark normal to wet intervals with (w) inset to indicate very wet periods. M signals periods of moraine development, Cd indicates cooler moister climate and Wm indicates warmer climate in the Canadian Rockies (Luckman, 1993; Luckman *et al.*, 1997).

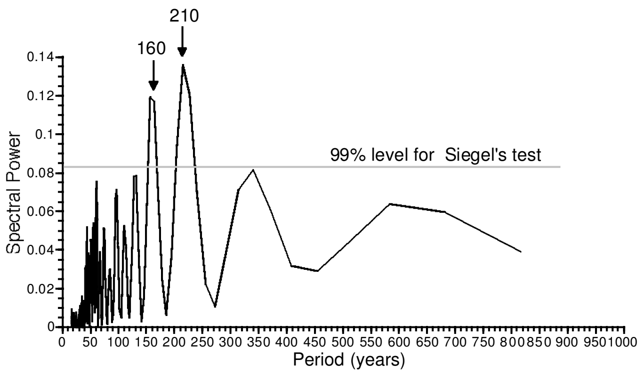

Figure 7 Spectral analysis of the raw Dog Lake CHAR time series using SPECTRUM (Schulz and Stattegger, 1997). This program allows for the use of unevenly spaced data in time and avoids interpolation or resampling methods, which can introduce red noise in spectral results. Dominant periods at ~160 and ~210 years are marked by arrows and are significant at the 99% level on the basis of Siegel's test (Siegel, 1980).

Whitlock, 2001; Long *et al.*, 1998), northern California (Mohr *et al.*, 2000), Wyoming (Millspaugh and Whitlock, 1995; Millspaugh *et al.*, 2000) and British Columbia (Gavin, 2000; Hallett, 2001). Most studies report fire-frequency changes associated with Holocene climate.

CHAR records from continuous lake sediment do not display an erasure effect and have the potential to record all fires around the lake over long timescales (Clark, 1990; Millspaugh and Whitlock, 1995). Lake-sediment records are weakened by chronological errors when dating with radiocarbon techniques and volcanic tephra layers. Despite these concerns, most CHAR peaks can be matched with stand-age data around the lake, and this expected result is well supported by modern studies of charcoal deposition in lake sediments after fires (Clark *et al.*, 1998; Gardner and Whitlock, 2001; Whitlock and Millspaugh, 1996). The prominent peak at *c.* 1800 corresponds to a large 22.7 km^2 stand-destroying fire around the lake. The CHAR peak representing a small 0.05 km^2 at *c.* 1980 fire on the east side of the lake appears as a small 0.2 particles cm^{-2} yr^{-1} signal. If this size relationship exists for CHAR peaks in the past then we can safely say that the larger CHAR peaks in around *c.* 1120 and *c.* 1180 were large fires close to the lake. However, it is difficult or misleading to try to determine the size and extent of past fires from the broad range of CHAR peak values at Dog Lake and presumably other lake sites (Figure 5). CHAR peaks represent a complex spatial aggregation of local to extra-local fires in the watershed. In this study, nearby stand-origin dates, and to a lesser extent fire scars, were the best calibration tools for a CHAR record retrieved from a valley-bottom lake surrounded by mountains. Fires outside the immediate watershed, or downwind of the lake, are not well represented by CHAR data. Charcoal abundance is known to increase in lakes downwind of a fire (Gardner and Whitlock, 2001).

In Yellowstone National Park, with large plateaus and rolling subalpine forest, CHAR peaks appeared in lake sediments with unburned watersheds, implying that charcoal must have originated from extra-local fires (Millspaugh and Whitlock, 1995; Whitlock *et al.*, 1997). Large open tracts of forest in flat landscapes, such in the boreal forest (MacDonald *et al.*, 1991), may cause CHAR records to be even more spatially complex because winds can bring charcoal from distant fires. This study suggests that small watersheds in mountain valleys may be preferred sites for fire-history reconstruction. Multi-lake studies combining CHAR data with dendrochronological fire-history information are needed to address the temporal and spatial variability of forest fire in mountain valleys. Lakes with laminated sediments (Larsen and MacDonald, 1993; Larsen *et al.*, 1998) and simple watersheds in restricted mountain valleys would be preferable.

High-resolution sampling of laminated sediments revealed lags in charcoal deposition for ~20–40 years after a fire event. This is in agreement with other studies using non-laminated sediments (Whitlock *et al.*, 1997; Whitlock and Millspaugh, 1996) and suggests marking a fire event at the beginning of a CHAR peak (Hallett and Walker, 2000; Long *et al.*, 1998; Millspaugh and Whitlock, 1995; Millspaugh *et al.*, 2000; Mohr *et al.*, 2000). Magnetic susceptibility was not as useful for identifying erosion after fires around Dog Lake because only the large fire at *c.* 1800 showed an increase in minerogenic material. Other fires lacking a magnetic susceptibility increase may not have been as severe (or local to the lake) as in *c.* 1800. Magnetic susceptibility peaks have been used to identify erosion after a disturbance, such as a fire or flood event (Millspaugh and Whitlock, 1995; Thompson and Oldfield, 1986) or the presence of a (thin) hidden volcanic tephra layer (Hallett *et al.*, 2001).

Charophyte macrofossils as indicators of lake-level change

The restriction of oospores to *Chara globularis*-type in Dog Lake prevents interpretations of water-level changes based on interspecific environmental requirements (Haas, 1994; 1999). On decade to century timescales, the distribution of charophyte growth in a lake basin may be affected if water levels change by a metre or more (Haas, 1999). *Chara globularis*-type charophytes are eurythermal with indifferent light requirements, and a pH range from 6.8 to 8.2. They are found at elevations up to 2000 m and live at water depths from 0 to 10 m, but tend to prefer the 0–4 m depth zone (Haas, 1994). Dog Lake satisfies all these growth requirements and one would expect the entire lake basin to be covered in *Chara globularis* late in the summer. However, the shallow 1–3 m portions of Dog Lake are currently free from charophytes, which are restricted to the deepest portion of the lake between 4 and 4.7 m.

We propose that other biotic or abiotic pressures are limiting charophyte growth in the 0–3 m water depths. Herbivory of charophytes by Amphipods (scuds) such as *Hyalella aztec* and *Gammarus lacustris* is common in the shallow waters of western Canadian lakes (Anderson and Raasveldt, 1974). However, below 3 m of water depth herbivory of charophytes by scuds becomes very restricted and overall growth is less affected by grazing pressure (Mann *et al.*, 1999; Proctor, 1999). At depths greater than 3 m, water is cooler and disturbance by wind currents and wave turbulence on the sediments is reduced. A lowering of water levels in this flat basin would cause an increase in the area of the 0–3 m 'scud zone' and expand the range of grazing pressure to areas where charophytes are growing in dense mats. Lower water levels and increased temperatures would reduce thermal stratification in the lake and expose charophytes to a less favourable environment. This warming, along with increased wind currents and wave turbulence, would present an added challenge to charophyte growth. A combination of all these biotic and abiotic pressures during low water levels would reduce optimal growth area for charophytes and restrict them to the deepest portions of the basin.

Airphotos of Dog Lake from *c.* 1952 and 1958 have a large dark area of deep water and dense charophyte growth in the current 3–4.7 m portions of basin. Lighter charophyte-free sediment is seen along the shallow edges of the lake. Denser charophyte growth over the coring site in *c.* 1952 and 1958 is in agreement with a slightly higher oospore accumulation rate value of 0.2 for this time period. Currently charophytes are growing in a limited area just in the deepest 4–4.7 m portion of the lake and large areas of the 1–4 m zone are clear of charophyte growth with barren areas of light-coloured calcareous sediment visible in 1978 and 1995 air photos. Lower water levels and/or warmer temperatures of the twentieth century (Crowley, 2000; Esper *et al.*, 2002; Jones *et al.*, 2001) over the past few decades may have increased the area of the 'scud zone' where grazing pressure limits charophyte growth in the lake. The palaeoecological record of inferred water-level change at Dog Lake suggests that monitoring of charophyte growth area, water level, the effects of scud herbivory and water temperature would be useful at this lake site and others. High-inferred water levels during solar (sunspot) minima and lower water levels during solar maxima suggest a response to climate and solar variability. This association should be tested at other sites in the region. Reconstructed lake-level changes are useful for reflecting large-scale circulation features and climatic change in the past (Harrison and Metcalfe, 1985). A broad distribution of sites would increase our understanding of the potential impacts of global warming on fire regimes and water balance in British Columbia.

Comparison of regional climate, fire history and lake-level records

In general, there is an interesting inverse relationship between CHAR peaks and *Chara* oospore accumulation rates in the last 1000 years at Dog Lake. This relationship suggests that past climatic variability may affect both fire events and lake-level changes. Our results seem to corroborate numerous palaeoclimate studies in the Canadian Rockies and western North America during the last 1000 years. For example, frequent forest fires and lowered lake levels support evidence of warmer and drier climate during the 'Mediaeval Warm Period' (MWP). Frequent CHAR peaks from *c.* 980 to 1300 suggest that several fires disturbed forests around the lake during this period and a warmer and drier climate than today. High-resolution pollen ratios from ~AD 900 to 1250 show evidence of dry-open forest type dominated by *Pseudotsuga*-*Larix* and Poaceae, and prominant CHAR peaks during this period (Hallett and Walker, 2000). The large CHAR peak beginning at *c.* 1120 appears similar in magnitude to the large 22.7 km^2 stand-destroying fire documented by both stand ages and CHAR data at *c.* 1800 (Figure 6). These two CHAR peaks like the *c.* 1610 and *c.* 1800 fires also occur during century-scale solar irradiance maxima and may reflect more persistent high-pressure circulation in the summer months (Haigh, 1996; Shindell *et al.*, 1999).

Frequent forest fires and low lake levels at Dog Lake during the MWP corroborate with other studies from this region and western North America. For example, growing conditions for trees at high elevations were more favourable during the AD 950–1100 period in the Canadian Rockies (Luckman, 1994). High fire frequencies also occur in the giant sequoia forests of the Sierra Nevada between AD 1000 and 1300 (Swetnam, 1993) and tree-ring data from subalpine conifers in the Sierra Nevada indicate that summer temperatures exceeded late twentieth-century values between AD 1100 and 1375 (Graumlich, 1993). Except for a brief period from *c.* 980 to 1000 and from *c.* 1040 to 1100, coeval with the Oort solar (sunspot) minimum, charophyte-inferred lake levels appear low for most of the MWP. Lake-level reconstructions in the Sierra Nevada (Li *et al.*, 2000; Stine, 1994) show persistently dry climate for much of the MWP from ~*c.* 900 to 1300 (Figure 6). The agreement between these palaeoenvironmental records over the last 1000 years suggests that large-scale regional circulation patterns, such as an intensified Pacific High, may be responsible for dry summer conditions at Dog Lake during the MWP.

In areas such as the Northern Great Plains, where circulation patterns are more complex and influenced by variable Pacific, cold dry Arctic and moist tropical air masses from the Gulf of Mexico, we see highly variable climate (Lydolph, 1985). Reconstruction of lake-water salinity in the Northern Great Plains show dry conditions at Moon Lake during the MWP (Laird *et al.*, 1996), although variations in local hydrology at other sites suggest that both the MWP and 'Little Ice Age' (LIA) were hydrologically complex (Fritz *et al.*, 2000). Records of salinity and aridity in the Northern Great Plains nevertheless suggest that climate may be influenced by century-scale solar forcing (Yu and Ito, 1999). Statistically significant periodicities of ~210 and ~160 years in the Dog Lake CHAR record corroborate evidence of solar forcing of climate from the Northern Great Plains. However, dry cold periods in the Northern Great Plains appear to be in phase with solar minima and cold events in Greenland (Yu and Ito, 1999), which may indicate enhanced Arctic circulation. Higher inferred lake levels and less frequent fire during solar minima, such as the Oort, Wolf, Spörer and Maunder, suggest that Dog Lake is largely dominated by Pacific circulation. Areas closer to the Pacific coast and west of the continental divide are more likely to have climate influenced predominantly by Pacific air masses (Lydolph, 1985; Thompson *et al.*, 1993).

After *c.* 1240 we start to see evidence of deteriorating climate in the Canadian Rockies with a cold period and glacier advances that killed trees at Robson and Peyto glaciers (Luckman *et al.*, 1997). CHAR peaks decrease dramatically and inferred lake levels start to increase at Dog Lake (Figure 6). Pollen ratios indicate a shift from dry-open forests to a wet-closed forest type around Dog Lake beginning *c.* 1300 and do not approach modern levels until around *c.* 1800 (Hallett and Walker, 2000). By the late 1400s, we can compare high-resolution dendroclimate records from south-eastern British Columbia with the Dog Lake records. Although our sediments records have coarse decadal sampling, we see some evidence of concurrent dry climate *c.* 1470–1510, *c.* 1560–1570 and *c.* 1630–1650, and a major wet interval *c.* 1520–1550 in the southern Rockies (Watson and Luckman, 2001). A fire at *c.* 1490 followed by a rise in charophyte inferred lake levels at *c.* 1520 and subsequent low water levels and another fire in the mid-1600s are supported by dendroclimate results (Figure 6). Subalpine tree-ring data from the Sierra Nevada show a period of cold temperatures from *c.* 1450 to 1850 which corresponds to the LIA (Graumlich, 1993). Long multidecadal drought patterns were characteristic of the western interior of Canada prior to the twentieth century (MacDonald and Case, 2000) and the Great Plains of the United States prior to *c.* 1600 (Woodhouse and Overpeck, 1998). Climatic changes inferred from fire activity and lake-level changes at Dog Lake appear to indicate fluctuating dry and wet intervals during the LIA. These low-frequency precipitation variations are common in dendroclimate records and are probably controlled by synoptic or larger-scale circulation patterns (Watson and Luckman, 2001). Changes in global atmospheric circulation beginning *c.* 1400 and during the LIA were characterized by variability in meridional strength with persistent cooling and storm activity (Kreutz *et al.*, 1997).

At Dog Lake, an increase in lake levels and an abrupt decline in fire activity occurs after *c.* 1680 through the mid-1700s (Figure 6), which is coeval with the Maunder solar (sunspot) Minimum, when Northern Hemisphere temperatures were cooler due to decreased solar irradiance (Luterbacher *et al.*, 2001; Shindell *et al.*, 2001). There are glacial advances and moraine-building features dated to this cool and wet period, and these conditions occur again in the mid-1800s representing important events at the end of the LIA (Luckman, 1993; Luckman *et al.*, 1997). During the 1700s several dendrochronological fire-history studies report fire-frequency changes around *c.* 1788 in the Kootenay National Park (Masters, 1990) and *c.* 1730 in southern Alberta (Johnson and Larsen, 1991), and ~1760 in Glacier National Park, British Columbia (Johnson *et al.*, 1990) indicating that LIA climatic changes had an important impact on fire regimes in the region. Undoubtedly, there is much variability in fire response in Kootenay National Park because a major fire occurred at *c.* 1720 (Figure 3), but around Dog Lake conditions were relatively wet and fire-free during this period.

Major drought occurred during the 1790s in the Canadian Rockies (Watson and Luckman, 2001) and in the northern Great Plains of the United States (e.g., Duvick and Blasing, 1981). The timing corresponds well with a large stand-destroying fire around the lake *c.* 1800 and later dry periods may have promoted fires at *c.* 1808, 1820 and 1828. Lake levels at Dog Lake were again high through the mid-1800s while glaciers again advanced in the Rockies (Luckman, 1993; Luckman *et al.*, 1997); however, fires did occur at *c.* 1851 and 1868 north of the lake. The last dry period around the lake occurred during *c.* 1880–1930 and includes well-documented drought intervals in the *c.* 1890s and *c.* 1930s (Watson and Luckman, 2001). One of the largest fires in Kootenay National Park that occurred in *c.* 1917 reached the forest just 5 km south of the lake (Figure 3). In the late twentieth century, water levels appear to rise until the mid-1970s. Soon after, yet another low water level period begins in *c.* 1980, indicating a return to drier climate (Figure 6). Fires around the lake at *c.* 1956 and *c.* 1980 are small (Figure 3) and relatively insignificant during the last few decades of the twentieth century. Periodically, larger fires have occurred according to the palaeoecological record at Dog Lake. The dendrochronological fire-history work of Masters (1990) reported extremely low fire frequency for the late twentieth century and attributed this to increased precipitation in the area. The impacts of fire suppression in Kootenay National Park were not considered effective until the use of helicopters in the *c.* 1950s. If the past CHAR record is the key to the future, then we should expect more large stand-destroying fires in the Kootenay Valley. Temperature variations over the last millennium prior to *c.* 1850 were largely due to changes in solar irradiance and volcanism (Crowley, 2000). A twenty-first-century global-warming projection now exceeds the natural variability of the last 1000 years. Further warming may increase both the frequency and extent of fires in southern British Columbia.

Conclusions

This study demonstrates the importance of reconstructing the long-term variability of fire regimes in southern British Columbia. Combining stand-age information with high-resolution charcoal records from lake sediments is the best method for answering long-term questions of natural variability in forest disturbance regimes, vegetation composition and climate. CHAR peaks at Dog Lake correspond well with the time-since-fire map for the Kootenay Valley (Masters, 1990) and add support to charcoal-based fire-history reconstructions. Large fire events around the lake occurred during century-scale solar irradiance maxima around *c.* 1800, the early 1600s and during the MWP. Variations in charophyte macrofossil accumulation rates suggest that lake levels have fluctuated along with climate over the last 1000 years. The shape of the basin and the depth of the 'scud zone' may have an important impact on the growth of charophytes in the lake and can be used to infer past lake-level changes. Lake-level variability may be linked to climate via large-scale circulation changes and, potentially, the impacts of century-scale solar irradiance variations. Further work is needed to build a network of sites that expand our knowledge of past disturbance in various forest types and lake-level variability across the region.

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