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Abstract: A Holocene record of climate, fire and vegetation regimes was reconstructed for Siesta Lake, Yosemite National Park, California, using fossil pollen and charcoal from lake sediments. These reconstructions were generated to provide a long-term perspective on drought in the Sierra Nevada. The sedimentary record is in agreement with other long-term records of climate and vegetation from the Sierra Nevada, and the records of climate and fire for the last *c.* 1000 years are in agreement with tree-ring and hydrological studies. This correspondence suggests that sedimentary charcoal and pollen are reliable indicators of change in climate, vegetation and fire frequency through time. The fire frequencies associated with the droughts of the 'Mediaeval Warm Period' are only half as great as those recorded during the early-Holocene insolation maximum. Model results suggest that the temperature increases associated with the insolation maximum are a good analogue for those expected with global warming. If this is the case, future droughts may be more severe than any experienced in the last several thousand years, and these data should be considered in planning for future change.

Key words: Palaeoecology, charcoal, pollen, drought, fire frequency, 'Mediaeval Warm Period', Holocene, Sierra Nevada, California.

Introduction

Numerous studies have been conducted to evaluate the last millennium of climatic variability in the Northern Hemisphere (Mann *et al.*, 1998; 1999; Jones *et al.*, 1998). Such research provides a hemispheric context for understanding drought cycles in California over the last thousand years (Stine, 1994; Graumlich, 1991; 1993). Several studies have expressed concern that with increased temperatures caused by global warming, drought will become a more prevalent problem in California (Knox, 1991; Vaux, 1991; Botkin *et al.*, 1991). In order to predict the climatic and ecological response to global warming, it is helpful to look at a climatic analogue to greenhouse warming and see how systems responded to increased warmth in the past (Flannigan *et al.*, 1998). Although not a global climatic phenomenon (Hughes and Diaz, 1994), the 'Mediaeval Warm Period' (*c.* 600–900 cal. yr BP) is a period of time during which the Sierra Nevada experienced warmer than present summer temperatures (*c.* 0.5°C) (Graumlich, 1993) and may provide a suitable analogue for how systems might respond to future global warming. Tree-ring records of climate in the Sierra Nevada indicate that the 'Mediaeval Warm Period' sustained the largest droughts of the last thousand years (Graumlich, 1991; 1993), which has also been supported by analyses of relict tree stumps from lakes (Stine, 1994). Palaeoecological studies have also been conducted to reconstruct past climates in the Sierra Nevada (Anderson, 1990; Anderson and Smith, 1994; Davis *et al.*, 1985; Davis and Moratto, 1988; Smith and Anderson, 1992). These studies provide a much longer record of climatic change, but most of these records rely on macrofossil and pollen analyses, which are often less sensitive than tree-ring analyses for recording rapid changes in climate (Bradley, 1999).

Recent research in the Sierra Nevada (Anderson and Smith, 1997), including sedimentary charcoal from Siesta Lake in Yosemite National Park (Brunelle, 1997), has contributed to palaeoclimatic reconstructions in California. Macroscopic sedimentary charcoal analyses provide a record of local fire for the

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watershed, which may be sensitive to shorter-term fluctuations in climatic variability. Numerous investigations have demonstrated that certain weather phenomena such as drought and high winds lead to increased probability of fire (Swetnam, 1993; Johnson and Wowchuk, 1993; Bessie and Johnson, 1995; Flannigan *et al.*, 1998). On palaeoecologic timescales, Terasmae and Weeks (1979) proposed that records of fire as preserved by charcoal in lake sediments might provide information on past climate. The temporal resolution of sedimentary charcoal ranges from annual (laminated sediments) (Smith, 1989) to subcentennial (Mohr *et al.*, 2000), and macroscopic charcoal records provide the opportunity to evaluate the climate on millennial timescales. This long-term perspective can provide an indication of the range of natural variability of drought and fire occurrence, which may be important when planning for future climatic change.

We report here on research from Siesta Lake in Yosemite National Park, and concentrate our discussion on the record of the last thousand years and how it relates to the early Holocene. This research is part of an ongoing initiative that seeks to determine the palaeoenvironmental history of the largest mountain range in California – the Sierra Nevada.

The site

Siesta Lake is a small pond located in Tuolumne County, California (37°51′ N, 119°40′ W, 2430 m; Figure 1). The pond (surface area ~0.13 km^2) is contained by morainal deposits, formed most recently by a Tioga-age ice advance. The glacier occupied the Siesta cirque to the southeast, and terminated immediately south of the modern Tuolumne River canyon (Huber *et al.*, 1981–85).

At the time of lake coring (October 1995), maximum depth was measured at 1.35 m and the average depth was approximately 0.81 m. Inflow comes from snowmelt in the cirque from the southeast. The approximate area of the modern drainage basin of the pond is 11.83 km^2 (Huber *et al.*, 1981–85). The forest generally grows to the shore of the lake, and the shallow lake margins are dense with aquatic species such as sedge (*Carex* sp.), rush (*Scirpus*) and water lily (*Nuphar*).

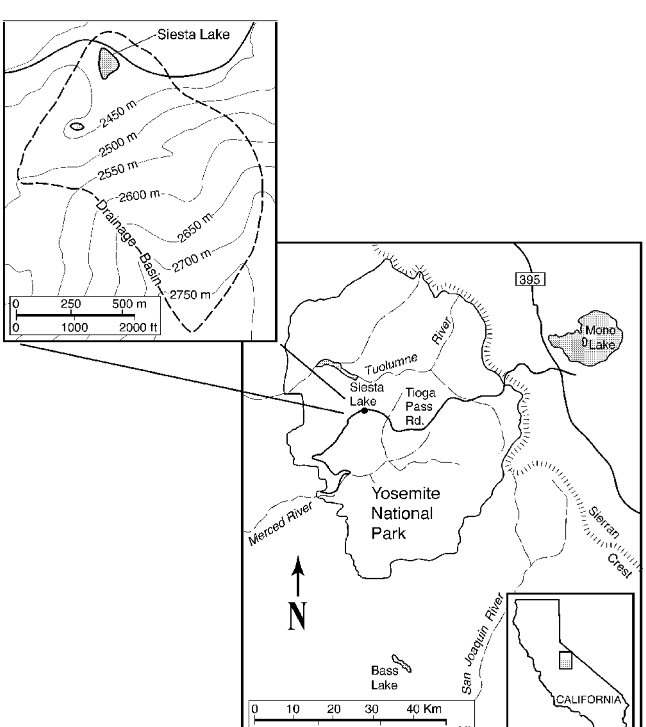

Figure 1 The lower panel indicates the location of Siesta Lake in Yosemite National Park. The upper panel shows the delineation of the watershed and the location of the lake.

Siesta Lake lies in the upper montane forest zone (Rundell *et al.*, 1988), surrounded by a lodgepole pine (*Pinus contorta* ssp. *murrayana*) forest. Sierran lodgepole pine forests often occur in moist areas in glacially scoured terrain (Rundell *et al.*, 1988). Red fir (*Abies magnifica*) and an occasional western white pine (*Pinus monticola*) are also present in the drainage basin around Siesta Lake. Presently, Siesta Lake is near the upper elevational extent of red fir. As at other locations dominated by Sierran lodgepole pine forests, there are few herbaceous and shrubby understorey species, and little litter accumulation (Rundell *et al.*, 1988). However, occasional openings within the forest allow species such as huckleberry oak (*Quercus vaccinifolia*), kinnikinnick (*Arctostaphylos nevadensis*), gooseberry (*Ribes montigenum*) and mountain heather (*Phyllodoce breweri*) to thrive (Rundell *et al.*, 1988).

Vegetation in the upper montane red fir forest, occurring primarily at elevations below the lake (*c.* 1800–2750 m), includes red fir, white fir (*Abies concolor*) and occasionally mountain hemlock (*Tsuga mertensiana*). At elevations higher than the lodgepole pine forest is the subalpine forest (*c.* 2400–3050 m). Common tree species within this elevational range include mountain hemlock, western white pine, lodgepole pine and Sierra juniper (*Juniperus occidentalis* ssp. *australis*) (Rundell *et al.*, 1988).

Fire is an important component of most Sierra Nevada forests. Fires are frequent in the upper montane forest, but are typically of small spatial extent (Skinner and Chang, 1996). Fires in the upper montane zone are usually self-limiting because of the discontinuity of fuels created by bedrock exposures, the compactness of the fuels and the short fire season. The short fire season is a result of persistence of winter snow at higher elevations (Skinner and Chang, 1996).

Major (1988) describes the climate of California as zonally subtropical (33–42° N latitude). Beginning in the late spring, rapid heating of the land mass creates a temperature gradient between the ocean and land, which obstructs the Pacific air masses from moving onshore. The northern position of the Pacific subtropical high during the summer also prevents California from receiving much summer precipitation. Most summer moisture comes as a result of convective thunderstorms and an occasional storm from the south or southwest (Anderson, 1990).

In the winter the Pacific subtropical high moves southward, which places California in the path of low-pressure systems brought by the westerlies. The temperature gradient between ocean and land is reduced, allowing storms in the Pacific to move onshore (Mitchell, 1976). Thus, most of California's precipitation occurs during the winter, which in the montane zone comes as snow (Rundell *et al.*, 1988). Snow is not evenly distributed across the landscape because of drifting caused by wind (Major, 1988).

There are also possible impacts of El Niño/Southern Oscillation (ENSO) in the Sierra Nevada. Schonher and Nicholson (1989) examined annual rainfall during 11 ENSO events from 1882 to 1950 in California. The response to ENSO was regionally specific. Most years with extremely wet conditions are ENSO years, and the tendency for an ENSO event to increase rainfall is greatest in southern California. The pattern is more complex in central California where ENSO often results in abnormal rainfall (either higher or lower than normal). Northern California and the Sierra Nevada are the least consistently affected by ENSO today. However, Cayan (1996) demonstrated that ENSO conditions create snow water equivalent anomalies in the Sierra Nevada, but they do not exceed the 90% confidence interval for a two-tailed t-test. Also, palaeoecological data from meadows in the central Sierra Nevada, and data from the Siesta Lake study, demonstrate that increased moisture and fire frequency are contemporaneous with the onset of ENSO circulation around 5000–6000 yr BP (Anderson and Smith, 1997; Markgraf and Diaz, 2000).

Methods

Siesta Lake was cored in October 1995. A single short core (core 1) that retrieved the uppermost, unconsolidated sediments was collected with a Plexiglas™ tube outfitted with a coring head and piston. This core (total of 46 cm long) was sampled in the field in 1 cm increments and placed in whirlpack bags. Two long cores (core 2, 272 cm; core 3, 267 cm) were obtained using a modified Livingstone corer. Each drive was extruded in the field, wrapped in plastic wrap and aluminum foil, and stored in a wooden core box. All core samples were ultimately placed in cold storage at the Laboratory of Paleoecology at Northern Arizona University.

Pollen samples were taken at 5 cm intervals in core 1, from the top to a depth of 29.5 cm. Samples from core 2 were taken every 10 cm to a depth of 270 cm. One cubic centimetre (cc) pollen samples were processed using a modified Faegri *et al.* (1989) method. Samples were preserved in silicon oil. Duplicate pollen counts were made in the overlapping portion of core 1 and core 2. The core stratigraphies were then compared by matching the pollen data from each core, as well as the occurrence of a volcanic ash at 26–27.5 cm depth. This allowed for the designation of a composite core, which included counts from core 1 and core 2. In the resulting composite core, samples to a depth of 29.5 cm are from core 1, with all others taken from core 2. Each pollen sample was examined at 400 ×. Pollen samples were counted to a minimum of 50 non-*Pinus* terrestrial grains due to high concentrations of *Pinus* pollen.

A 5 cc sediment sample was taken from every linear cm of the composite core for charcoal analysis to provide a contiguous record of charcoal influx into the lake. Each sample was analysed by the methods in Millspaugh and Whitlock (1995), using 125 and 250 micron sieves to separate macroscopic remains from the sediment matrix. Millspaugh and Whitlock (1995) selected these size particles because the fire record documented by the >125 micron particles agreed with historic fire information from one of their study lakes. In addition, these size fractions were consistently present in most samples but not so numerous as to make counts unwieldy (Millspaugh and Whitlock, 1995). Deviations from their methodology used here included: (a) using a sodium hexametaphosphate solution (50 g/l) rather than Calgon™, and (b) treating some samples with chlorine bleach. The bleach treatment was devised to eliminate invertebrate faecal pellets. After being sieved the first time, the 'pellet samples' were placed in a beaker with 10% solution of chlorine bleach, heated to *c.* 50–60°C for 5–8 minutes and then re-rinsed through the sieves. This process effectively eliminated the mucilaginous faecal material while leaving the charcoal intact.

For each sample, charcoal particles were identified and counted at a magnification of 10–70 ×. Material described as charcoal was uniformly black with an iridescent sheen and visible cell structure. Macrofossils were identified from the contiguous samples as well. Spot analysis of samples immediately prior to, and after, bleach treatment showed that the bleaching process sometimes damaged vegetative macrofossils and destroyed the chitinous macrofossils (i.e., *Chironomid* head capsules, *Daphnia* ephippia). Based upon these observations, it is recommended that macrofossils be counted and removed prior to treatment with chlorine bleach.

Because of the low concentration of organics at the bottom of the core, an AMS date was necessary to acquire a bottom date (243–257 cm). Two additional samples (from depths of 57–63 cm and 117–123 cm) were also submitted and required extended counting due to low carbon concentrations (Table 1).

The raw charcoal influx data was analysed utilizing charcoal analysis software from the University of Oregon that decomposes the charcoal-accumulation rate (CHAR) time series into two components. These components consist of a background component that together considers varying charcoal production and sedimentation and a peak component that is assumed to indicate fire events (Long *et al.*, 1998; Mohr *et al.*, 2000). The background component reflects changes in charcoal production and deposition in the watershed through time. Charcoal production can vary because of changes in vegetation type, and deposition rates can change if the amount of charcoal entering the lake from terrestrial or littoral sediment storage changes. Therefore, the background component is a measure of charcoal influx as a result of changes in vegetation (and therefore fuel loads), and surficial delivery process to the lake, as well as internal sediment deposition within the lake itself (Bradbury, 1996). The peak component represents the charcoal input from a fire event in the watershed. A fire event is defined as one or more fires that occur within the time frame of the sampling interval. For example, the sedimentation rate at Siesta Lake is approximately 50 years/cm. Since every sample is analysed for charcoal, the record has a resolution of *c.* 50 years. When the CHAR of a sample exceeds background by a predetermined amount or threshold ratio, that particular interval is designated as a peak. The threshold ratio is determined by visual inspection of the data and correlation of the recent sedimentary charcoal record with historic watershed fires.

The CHAR time series was created for Siesta Lake by interpolating charcoal concentration values (particles/cm^2) and deposition times (cm/yr) to pseudo-annual values, then aggregating these pseudo-annual values into 50-year time intervals. The 50-year interval was selected because it represents the shortest deposition time of the Siesta Lake record. This strategy allows the preservation of the CHAR, and the evaluation of the data at equally spaced time intervals (Long *et al.*, 1998; Mohr *et al.*, 2000).

The background component was calculated by applying a 500-year locally weighted moving average to the CHAR time series. A threshold-ratio value of 1.1 was then used to compare the background component to each individual 50-year CHAR value for that interval. Individual 50-year intervals with CHAR values exceeding the background CHAR assigned to that interval were designated as peaks. The binary series of peaks was then smoothed to produce a mean frequency of fire events/1000 years (Figure 2).

Results and discussion

Sediment chronology and lithology

An AMS bottom date for the Siesta Lake core of 13 207 cal. yr BP and two additional bulk-sediment dates provide the chronology for the Siesta Lake core (Table 1), which was created using a second-order polynomial (Figure 3). The lithology of the Siesta Lake composite core is composed of gyttja above 184 cm. Below 184 cm the sediments consist of interbedded sandy clays, silts and sands. Four undated volcanic tephras occur at 26–27.5 cm, 74.5 cm, 98.5 cm and 247–248 cm. Based upon sediment-accumulation rates, ages of these tephras are approximately 2750, 7000, 8700 and 13 200 cal. yr BP, respectively.

Pollen analysis

Thirty-nine pollen types and four spore types were identified from the Siesta Lake core. Although pollen was essentially absent below 210 cm, pollen preservation in the remainder of the core was excellent, with degraded pollen never amounting to more than 2% of the pollen sum. Based upon changes in the pollen assemblages we were able to identify four pollen zones, whose descriptions and interpretations are below. Factor analysis was used to

Table 1 Radiocarbon dates for Siesta Lake sediment samples

Laboratory number	Analysis type	Sample depth (cm)	C^{14} age (yr BP)	Calendar age (cal. yr BP)	1 Standard deviation (cal. yr BP)
Beta-98037	Radiometric standard (extended counting)	57–63	4970 ± 100	5710	5765–5605
Beta-98038	Radiometric standard (extended counting)	117–123	9050 ± 150	10005	10110–9920
Beta-88451	AMS	243–257	11280 ± 60	13207	13295–13128

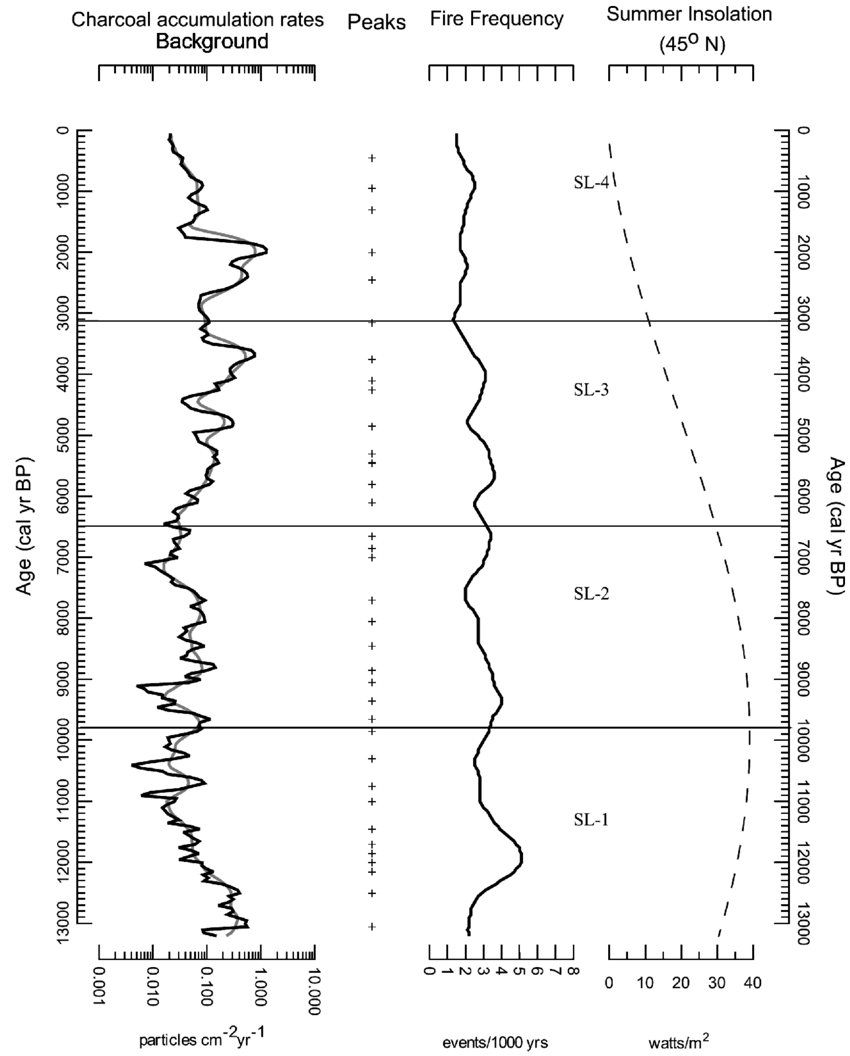

Figure 2 The left panel is the charcoal influx and background plotted on a log-scale. The peaks column indicates when influx exceeds background, and fire frequency represents the running local count of the fire peaks per 1000 years. Charcoal and inferred fire frequency data are plotted with the summer insolation anomaly for 45°N latitude.

help interpret the Siesta Lake pollen data. Results from the factor analyses were compared to both modern pollen studies (Anderson and Davis, 1988) and other palaeoecological studies in the Sierra Nevada (Davis *et al.*, 1985; Davis and Moratto, 1988; Anderson, 1990; Anderson and Smith, 1994). The Siesta Lake record extends over the last *c.* 13000 cal. years BP (Figure 4).

SL-1 (*c.* 13000–9750 cal. yr BP) pollen spectra are dominated by pine (*Pinus* sp.) pollen (averaging 72%). T-C-T pollen (Taxaceae-Cupressaceae-Taxodiaceae pollen types), perhaps either Sierra or common juniper, is abundant, as is mountain hemlock. Montane chaparral shrub pollen, such as bush chinquapin (*Chrysolepis*) and Ericaceae, is most common during this period. In addition, pollen of other shrubs, such as sagebrush (*Artemisia*; to 4.3%), Asteraceae (to 5.3%) and Poaceae (to 12.7%) are at their postglacial maximum. Pollen and spores of wetland plants, e.g., willow (*Salix*), sedge family (Cyperaceae), carrot family (Apiaceae), bistort (*Polygonum bistorta*) and shooting star (*Dodecatheon*), are at their maximum values, and spores of the quillwort (*Isoetes*) concentrations are high (Figure 4). Taken together, these assemblages suggest dry and open conditions. In the Sierra, dry and open environments contain an abundance of taxa such as T-C-T, bush chinquapin and Ericaceae (Anderson and Davis, 1988; Davis and Moratto, 1988). Although the upland taxa suggest dry/open conditions, the abundance of willow, sedge and members of the carrot family indicate abundant water. This probably represents the high lake levels due to the melting glacier in the cirque.

SL-2 (9750–6400 cal. yr BP) is also dominated by pine pollen.

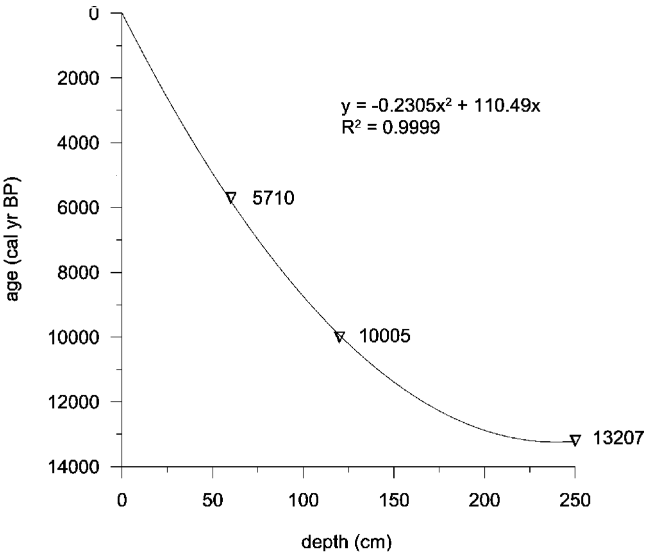

Figure 3 Siesta Lake chronology created with second-order polynomial. Triangles indicate radiocarbon dates and the associated age (cal. yr BP). Charcoal samples were analysed every centimetre of the core and pollen samples were analysed every 10 cm.

Fir (*Abies* sp.) pollen is at its Holocene minimum, and T-C-T pollen similarly declines. Bush chinquipin remains consistently present, and there is an increase in oak (*Quercus* sp.) pollen. These indicators suggest a decrease in effective precipitation, perhaps caused by increased summer insolation that may have resulted in warmer temperatures (Davis and Moratto, 1988; Anderson, 1990; Figure 4).

SL-3 (*c*. 6400–3000 cal. yr BP) continues to be dominated by pine pollen. Significant increases in fir and mountain hemlock occur, accompanied by equally significant declines in T-C-T pollen, and pollen of understorey shrubs and herbs (e.g., Ericaceae, bush chinquapin, Poaceae, Chenopodiaceae pollen types). These changes are consistent with an increase in effective moisture (Adam, 1967; Davis and Moratto, 1988; Anderson, 1990), and a significant closing of the forest canopy.

SL-4 (*c*. 3000 cal. yr BP to present) maintains consistently high percentages of pine, while fir pollen also reaches its maximum Holocene values. Needle fragments of lodgepole pine are consistently found during this period (not shown). Pollen of dwarf mistletoe (*Arceuthobium*) is also most abundant in this zone. Each of these indicates a further closure of the canopy around Siesta Lake. Dwarf mistletoe pollen is poorly dispersed so its presence in the pollen record indicates close proximity and local abundance (Anderson and Davis, 1988). Also, the spread of mistletoe is facilitated by dense tree canopy. These implications are supported by results from the factor analysis.

Charcoal record

The charcoal data from Siesta Lake was analysed using the methods in Long *et al.* (1998) and Mohr *et al.* (2000). As described, this technique consists of a statistical analysis of the CHAR, which allows for the identification of inferred fire events. Because the charcoal is analysed locally (window width 500 years), variables such as changes in vegetation type (and their effect on fuels) and erosional changes in the watershed at one point in the record do not influence the rest of the record (Mohr *et al.*, 2000).

CHARs vary throughout the Siesta Lake record. They start high at the beginning of SL-1, during the early stages of Siesta Lake.

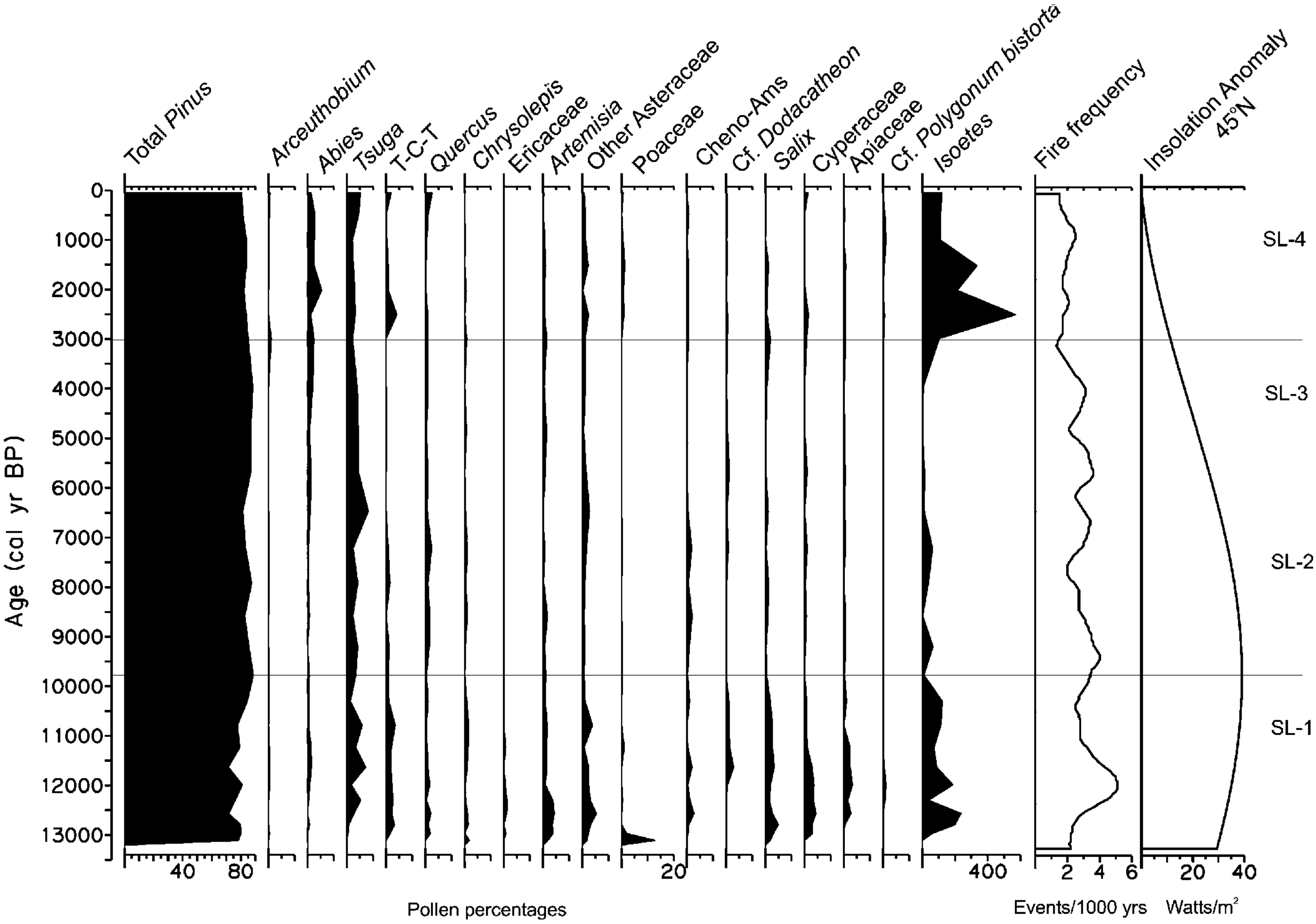

Figure 4 The pollen diagram for Siesta Lake plotted with fire frequency and the summer insolation anomaly for 45°N latitude.

The high accumulation rates at this time may be due to the herbaceous nature of the vegetation taxa represented by the pollen record and the dry, open conditions that they suggest. CHARs decrease toward the middle of SL-1 and stay low through SL-2 and into the early portions of SL-3. The low CHARs in zone SL-2 may be a result of the extended drought conditions that are suggested by the pollen taxa. Low effective moisture would limit fuel and, in turn, charcoal production. CHARs increase in the middle of zone SL-3, and into zone SL-4. This increase in CHARs is probably a result of increased effective moisture which would increase fuel production. CHARs decrease in the last half of zone SL-4, perhaps as a result of the drought associated with the 'Mediaeval Warm Period'.

The mean fire interval in the Siesta Lake record varies from a low of 0.5 fires/1000 years to 5.5 fires/1000 years (Figure 2). Though considerable variation occurs within the record, changes in fire regime are, in general, concurrent with changes in pollen zones. Fire-interval frequency is highest during SL-1, centred on 12000 cal. yr BP. Toward the latter part of SL-1, fire frequency declines to 2.5 fires/1000 years. Fire frequency again rises during SL-2, reaching nearly 4.0 fires/1000 years at *c.* 9400 cal. yr BP. However, during SL-3, fire frequency shows considerable variation, oscillating from 2.0 to 4.0 fires/1000 years, with frequency maxima at the beginning of the zone, and at *c.* 5600 and 4000 cal. yr BP. Fire frequency is lowest in SL-4, varying from 0 to 2.0 fires/1000 years.

Changes in fire frequency occur in conjunction with the vegetation shifts at Siesta Lake. The highest fire frequencies occur in SL-1 and SL-2 (mean = 2.79 fires/1000 years) when pollen evidence suggest that general conditions of the forests were more open and climate was presumably drier than today. Other Sierran records also support a drier early Holocene, including Davis *et al.* (1985), Davis and Moratto (1988), Anderson (1990) and Anderson and Smith (1994). Mensing (2001) provides a temperature and precipitation reconstruction for Owen's Lake, California, from *c.* 16000–8000 cal. yr BP, which also suggests that precipitation was below the modern mean and temperatures above the modern mean in the early Holocene (*c.* 10 500–8000 cal. yr BP).

Fire frequency continues to decrease through zones SL-3 and SL-4 (means = 2.52 and 1.39 fire events/1000 years, respectively). The time between shifts in fire occurrence are less in SL-3 than in previous zones, and the amplitude of the oscillation is also less (Figure 2). The curve suggests greater centennial-scale variability of fire occurrence from *c.* 6400–3000 cal. yr BP than before, or after, at Siesta Lake. This change in pattern corresponds to the beginning of a long-term increase in effective moisture as indicated by increases in fir pollen (Figure 4). Red fir (*Abies magnifica*) is favoured by increased soil moisture during the characteristically dry, Mediterranean-type summers (Rundell *et al.*, 1988; Barbour *et al.*, 1991) that have apparently dominated the region throughout the Holocene (Anderson, 1990; and others).

During the most recent 3000 years (SL-4), the fire frequency drops to below 2 fires/1000 years. Studies in the Sierra Nevada have demonstrated that increased effective precipitation occurred during the late Holocene, causing major changes within the forested communities. Changes included rising groundwater tables within montane meadows (Wood, 1975; Anderson and Smith, 1994), higher lake levels (Anderson, 1990) and continued forest closure (Anderson, 1990). Pollen and spore data from Siesta Lake are consistent with increased effective moisture, as shown by maximum percentages of fir pollen and an increase in aquatic and wetland types.

The Siesta Lake fire-history record shows striking similarities to records from montane meadows at lower elevations within the Sierra Nevada (Anderson and Smith, 1997; unpublished data). Although fire recurrence intervals were not calculated, the charcoal-accumulation rates for Sierran meadow sites showed significantly greater rates of deposition after *c.* 5100 cal. yr BP than before that time period. Charcoal-accumulation rates for the Siesta Lake record are also low in the early Holocene, but increase by 5000 cal. yr BP. Significant differences in accumulation rates occur during the last 2000 cal. years, however, with a decline at Siesta Lake, and an increase after *c.* 1200 cal. years ago in the meadow series.

The most recent millennium – comparison with high-resolution climate proxies

Several records of climate over the past 1000 years have been reconstructed using tree rings, relict stumps and multivariate approaches (Mann *et al.*, 1998; 1999; Jones *et al.*, 1998; Stine, 1994; Graumlich, 1993). These reconstructions have contributed to our understanding of past climatic variability, and are critical in comprehension of the nature of environmental changes associated with global warming. Multivariate analyses conducted by Mann *et al.* (1999) suggest a warmer Northern Hemisphere from *c.* 950–500 cal. yr BP ('Mediaeval Warm Period'), with cooler conditions initiated from *c.* 500–100 cal. yr BP ('Little Ice Age'). Tree-ring and hydrological studies from near Siesta Lake suggest a similar chronology of warming and cooling. Graumlich's (1993) high-elevation tree-ring record from the Sierra Nevada indicates warming from *c.* 850–575 cal. yr BP and cooling from *c.* 500–100 cal. yr BP, while Stine's (1994) study of Mono Lake fluctuations suggests warming from *c.* 1038–838 cal. yr BP and 740–600 cal. yr BP. Stine (1994) identified these two periods of drought as being particularly severe in comparison with droughts encountered in the last century and a half.

Observational data and tree-ring reconstructions of fire and climate suggest that effective moisture (and its effect on fuel moisture) is the dominant factor affecting fire regimes (Swetnam, 1993; Bessie and Johnson, 1995; Flannigan *et al.*, 1998; Veblen *et al.*, 1999). If the reverse relationship is true, we propose that past fire frequency is a powerful indicator of past moisture conditions, and long-term records of fire as reconstructed from sedimentary charcoal are important records of climate variability. The Siesta Lake fire-frequency index certainly provides an excellent example of this, in that it agrees with the other climate proxies that indicate periods of drought beginning about 1100 cal. yr BP, and lasting until *c.* 500 cal. yr BP.

The Siesta Lake index of fire frequency suggests that droughts from the early Holocene were considerably more extensive than those of the last 1000 years. The fire-frequency peak associated with the severe droughts of *c.* 1038 to 838 and 740 to 600 cal. yr BP is relatively small (*c.* 2.5 fire events/1000 years) when compared to peaks recorded earlier in the record (up to 5 fire events/1000 years, or twice as great). If, in fact, charcoal abundance or fire frequency does relate to effective moisture and can be used a proxy for climate, the severe droughts that allowed trees to take root in Lake Tenaya and Mono Lake (Stine, 1994) during the middle of the last millennium are small when compared with droughts experienced over the course of the last 13000 years.

This shorter-term drought associated with the 'Mediaeval Warm Period' is not as well recorded in the pollen data. Although longer periods of drought (early Holocene) and increased effective moisture (mid-Holocene) are recorded by changes in pollen taxa, this recent drought is not represented by significant changes in the pollen percentages. This suggests that the fire regimes (as recorded by sedimentary charcoal) may be more sensitive to short-term (millennial and submillennial scale) fluctuations in climate than vegetation.

Implications for the future

The 'Mediaeval Warm Period' is a Northern Hemisphere climate anomaly where the average temperature during the period (*c.* 900–500 cal. yr BP) was approximately 0.5°C warmer than the rest of the last thousand years (Mann *et al.*, 1999). Although the registration of the 'Mediaeval Warm Period' is not spatially homogenous (Hughes and Diaz, 1994), it is well documented in the Sierra Nevada (Graumlich, 1993; Swetnam, 1993; Hughes and Diaz, 1994; Stine, 1994).

Studies conducted in California suggest that the 'Mediaeval Warm Period' produced significant phases of drought that were long enough in duration to allow trees to encroach on retracting lake basins and become mature before being drowned by increasing lake levels. Stine (1994) suggested that these periods of drought were between 100 and 200 years long based on relict tree-stump analysis. Because California currently experiences significant water-availability issues, there is concern that changes in climate due to greenhouse warming could intensify these problems (Knox, 1991).

Sedimentary charcoal data from Siesta Lake represent the fire history for that watershed. Periods of high fire frequency from the last 1000 years of the record strongly correspond to the drought periods reconstructed by tree-ring and relict tree stump analyses (Graumlich, 1993; Stine, 1994). The relationship between known drought periods and increased fire frequency suggests that it is effective moisture that impacts fire regimes, and periods of increased fire frequency at earlier times in the Siesta Lake record may indicate other periods of drought not recorded by other climate proxy.

Based upon our analysis using sedimentary charcoal as a proxy for effective moisture or drought, there is reason to be concerned about future water availability in California. Periods of fire frequency that are double the magnitude of the 'Mediaeval Warm Period' droughts, and of longer duration, have occurred during the last 13000 years at Siesta Lake. Changes in vegetation and fire-frequency increases at *c.* 9300 cal. yr BP appear to be contemporaneous with the 1.4–2.1°C temperature increase associated with the Holocene insolation maximum (Adam and West, 1983) (Figure 4). The fire frequency at *c.* 9300 cal. yr BP during the summer insolation maximum was nearly double those associated with the 'Mediaeval Warm Period'. If warmth and drought do indeed lead to fire, there are concerns for how fire regimes might respond to the increased temperatures associated with greenhouse warming. Models are currently predicting temperature increases of 2–4°C for California under a $2 \times CO_2$ environment which we will exceed in the next 100 years if emissions do not change (Hansen *et al.*, 1984; Leung and Ghan, 2000). Flannigan *et al.* (1998) demonstrate through the use of models that, for Canadian forests, the Holocene insolation maximum is a good analogue to future conditions resulting from greenhouse warming.

It is not unreasonable to predict that drought will be a concern for California in the coming years. In fact, a high-resolution climate model has been utilized to simulate the climate response to a $2 \times CO_2$ environment for the Pacific Northwest and California (Hansen *et al.*, 1984; Leung and Ghan, 2000). These results predict an average warming of between 2 and 4°C, with increased precipitation in the Pacific Northwest and decreased precipitation in California. The combination of increased temperatures and decreased precipitation will have the significant effects on winter snowpack (reductions of 50–90%), which will then significantly affect the volume of spring runoff and soil and fuel moisture (Leung and Ghan, 2000). This model output corresponds with the predictions of future drought intensity based on sedimentary charcoal reconstructions for the past as well as the model results of Flannigan *et al.* (1998) for Canada. In order to prepare for and understand the spatial pattern of future drought, additional long-term studies of fire history need to be conducted to understand the spatial variability of the drought history across California during the Holocene.

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