Vegetation and fire history since the Late Pleistocene from the Trinity Mountains, northwestern California, USA

Mark L. Daniels, R. Scott Anderson and Cathy Whitlock

(1Ecological Restoration Institute, Box 15017, Northern Arizona University, Flagstaff AZ 86011, USA; 2Center for Environmental Sciences & Education, Box 5964, Northern Arizona University, Flagstaff AZ 86011, USA; 3Quaternary Sciences Program, Box 5644, Northern Arizona University, Flagstaff AZ 86011, USA; 4Department of Earth Sciences, Box 173480, Montana State University, Bozeman MT 59717, USA)

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Abstract: A 267-cm sediment core spanning the past c. 15 200 cal. yr was recovered from Mumbo Lake, in the Trinity Mountains of northern California’s Klamath Region. Plant macrofossils and pollen detail local and extra-local vegetation history, while high-resolution charcoal analysis provides details on local fire history. For the first c. 3000 years, climate was colder and drier than present, and supported an open, subalpine parkland vegetation, with low fire frequencies and fuel biomass. From c. 12 100 to 9800 cal. yr BP increasing moisture and soil development led to a woodland community with three new pine species invading the basin. Fire frequencies remained low, but individual fires may have been more intense because of increased fuel loads. Between c. 9800 and 7200 cal. yr BP, climate warmed and dried considerably, allowing for the expansion of oak and other chaparral species. Fire frequencies increased in the early Holocene, but low charcoal accumulation rates suggest a frequent, relatively low-intensity fire regime. From c. 7200 to 3800 cal. yr BP, climate became cooler and moister again. Many conifer species appeared for the first time, and chaparral species maintained a strong presence. The fire record shows a dramatic increase in charcoal accumulation rates as well as an increase in fire frequency. From c. 3800 cal. yr BP to present, more conifer species enter the record, and abundance of chaparral species gradually diminishes to present levels.

Key words: Klamath, pollen, charcoal, fire, climatic change, vegetation change, Trinity Mountains, California, Late Pleistocene, Holocene.

Introduction

The Klamath region comprises a complex set of mountain ranges in northwestern California and southwestern Oregon. With its diverse geologic history of subduction, volcanism, accretion, deposition and intrusion, the area exhibits a wide range of rock and soil types across a broad elevational gradient from sea level through almost 2800 m (Schoenherr, 1992). The floristic composition is particularly rich, because of this combination of edaphic and elevational diversity and the transitional climatic and physiographic nature of the region. Located where the Mediterranean climate of California grades into the more mesic Pacific Northwest climate, the region boasts relatively mild temperatures and plentiful precipitation, and supports elements of the floras from both the north and south. The area also forms a mountainous bridge between the Coast Ranges of California and Oregon, and the loftier Cascades inland, allowing for mixing of coastal and interior mountain floras. The end result is a regional flora unrivalled in its diversity across the American West, which has been called ‘central’ to the other western floras in the same way that the Appalachian Mountains are to the East (Whittaker, 1961).

The Klamath region has been the site of a number of palaeoecological studies. Heusser (1960) conducted a large-scale study of pollen records along the Pacific coast from Alaska to northern California, including three sites along the...
western and southern edge of the area. Miller et al. (1976) describe a pollen record from Campbell Lake, in the northwestern part of the region. West (1989, 1990) reported the results of a pollen study from Cedar Lake, near the eastern edge of the region, and compared it with other records from the nearby California Coast Range. Mohr et al. (2000) described the vegetation, fire and climate history from Bluff and Crater lakes in the eastern part of the area based on pollen and high-resolution charcoal data. Wanket (2002) described pollen and charcoal records spanning the last 23 000 years from Twin Lake, in the western part of the region. Briles (2003) also utilized pollen and high-resolution charcoal analysis to describe the vegetation and fire history from Bolan Lake, near the northern edge of the area. In this paper we present pollen and high-resolution charcoal records from Mumbo Lake, to the south of Bluff and Crater lakes, and very close to Cedar Lake (though with a different exposure), to reconstruct the local vegetation and fire history. These data are compared with published records to better understand the climate, vegetation and fire history of the Klamath region.

**Setting**

Mumbo Lake occupies a small cirque basin at Lat. 41°11′27″ N, Long. 122°30′36″ W in the Trinity Mountains, California, near the eastern boundary of the Klamath region (Figure 1). Precipitation in the area falls mainly as winter snow, though the site also receives moderate summer precipitation from convective thunderstorms. The nearest weather station is located in the town of Mt Shasta, approximately 20 km to the northeast at an elevation of 1080 m, and records mean daily low temperatures of −3.4°C in January and mean daily high temperatures of 29.3°C in July. Annual precipitation averages c. 100 cm, with all but 6.5 cm falling between October and May (climate data from the Western Regional Climate Center, http://www.wrcc.dri.edu, last accessed 29 June 2005). As Mumbo Lake, at 1860 m elevation, is considerably higher than the weather station, the local climate is correspondingly cooler and moister overall, and may be more heavily influenced by summer thundershers.

The lake is situated in a rich mixed-conifer forest on the ecotone between the *Abies concolor* vegetation zone and the higher elevation *Abies magnifica* zone (Sawyer and Thorburn, 1988). This transitional forest zone has also been described as the mixed subalpine forest series (Sawyer and Keeler-Wolf, 1995). Principal trees at Mumbo Lake include *Pinus contorta* var. *murrayana* (Sierran lodgepole pine), *Abies concolor* (white fir), *A. magnifica* (red fir), *P. monticola* (western white pine) and *Tsuga mertensiana* (mountain hemlock) (common and scientific names follow Hickman, 1993). Forest canopy around the lake is closed, although montane chaparral (including *Quercus vaccinifolia* (huckleberry oak), *Arctostaphylos* spp. (manzanita) and rosaceous taxa such as *Amelanchier utahensis*...
(serviceberry) and *Spiraea douglasii* (spiraea)) and bare rock cover much of the surrounding slopes. Logging operations in the twentieth century enhanced the natural openness of the basin, which is drained by Mumbo Creek, a small stream that flows into the Trinity River.

**Methods**

A 267-cm core was recovered from Mumbo Lake using a 5-cm-diameter modified Livingstone piston corer (Wright et al., 1984) and wrapped in plastic and aluminium foil in the field before storage in a refrigerated facility. A short core of 42-cm length was also collected to retrieve the sediment/water interface and investigate the most recent portion of the pollen and charcoal records; results of this study are reported elsewhere (Wick, 1996; Whitlock et al., 2004).

The core was split longitudinally and sediment lithology and colour were described. Samples of 1 cm$^2$ were taken at 10-cm intervals through the core and dried for 24 h at 90°C. The dried samples were then weighed and burned for 2 h at 550°C, with the weight difference used to calculate the organic content of the sediments (Dean, 1974).

Half of the core was sliced into contiguous 1-cm thick sections, and from each slice 8 cm$^3$ was packed into plastic vials. These samples were measured for magnetic susceptibility using a Sapphire Instruments cup-coil magnetic susceptibility device. Resulting data were converted into pseudo-annual rates and decomposed in the same manner as the charcoal accumulation data (see below for explanation), with peaks interpreted to represent large influxes of inorganic sediment from the basin or volcanic eruptions (Thompson and Oldfield, 1986).

Sediment samples of 1 cm$^3$ were taken at 10-cm intervals through the core and processed for pollen analysis following standard methods (Faegri and Iversen, 1989), with the addition of sieving clay-rich samples through a 7-μm mesh Niteq$^{	ext{®}}$ screen. Two *Lycopodium* spore tracer tablets (batch 124961) were added to each sample (Stockmarr, 1971) to allow for calculation of pollen concentration (grains/cm$^3$). Processed samples were mounted on microscope slides in silicone oil and counted at 400 × magnification. Identification was accomplished with the use of reference manuals (Kapp, 1969; McAndrews et al., 1973; Moore et al., 1991) and by comparison with reference collections at Northern Arizona University and the University of Oregon. *Pinus* grains were separated into haploxylon and diploxylon categories when preservation allowed, based on the presence or absence of verrucae on the leptoma of the grain. *Abies* and *Tsuga mertensiana* grains were differentiated from *Pinus* based on size and surface sculpturing elements. Deciduous and evergreen *Quercus* grains were also differentiated based on surface characteristics (Jarvis et al., 1992).

The pollen sum consisted of 300 or more upland terrestrial grains, including at least 50 non-*Pinus* grains, since all samples were dominated by *Pinus*. Aquatic and riparian pollen (including Liliaceae, Cyperaceae, Apiaceae, *Typha, Lappa* and *Salix*) and spores (including ferns and *Isoetes*) were not included in the pollen sum, although their abundances were calculated as percentages of the terrestrial pollen sum, for comparison within this category. Results were graphed using Tilia software, and pollen zones were constructed based upon the results of constrained cluster analysis utilizing the Tilia subroutine CONISS (Grimm, 1987).

Charcoal analyses followed the methods for high-resolution macroscopic charcoal analysis described by Long et al. (1998), Mohr et al. (2000) and Whitlock and Anderson (2003). The core was sampled in 1-cm increments and sieved through 125- and 250-μm screens, and charcoal particles collected on the screens were counted under 7–30 × magnification. The resulting data were converted into pseudo-annual charcoal accumulation rates (CHAR, particles/cm$^2$ per yr) by multiplying absolute concentration (particles/cm$^3$) by the sedimentation rate (cm/yr). CHAR data were then decomposed into a slowly-varying ‘background’ component (representing charcoal deposited from regional fires or stored in the watershed and slowly released) and a ‘peaks’ component (interpreted to represent local fire events). Parameters for the decomposition were selected by comparison of the CHAR record with results from the short-core study at Mumbo Lake (Wick, 1996) and dendrochronologic data collected from the basin around the site (Whitlock et al., 2004). Analytical parameters included (1) average sample interval of 37 years (corresponding to the average deposition rate per centimetre in the upper portion of the core); (2) a window width (for smoothing the CHAR curve) of 370 years; (3) a peak/mean threshold ratio of 1.0 (values exceeding this background concentration were counted as a ‘peak’); and (4) a window width of 1850 years for smoothing the fire event frequency curve.

Plant macrofossils (isolated conifer needle fragments) were recovered from 97 core levels during the initial core sampling as well as during charcoal analysis. Most of the needles belonged to the genus *Pinus*, and were identified to species under a dissecting scope based on needle shape, stomatal patterns and characteristics of internal anatomy (number and placement of vascular bundles and resin canals), as described in reference keys and manuals (Harlow, 1947; Anderson, 1987) and from sectioned specimens at Northern Arizona University’s Laboratory of Paleoeecology.

**Results and interpretation**

**Chronology and lithology**

The chronology was developed from five AMS radiocarbon dates (Table 1) and one tephra date (see below). An estimated age of 25 cal. yr BP for the top of the record was based on a correlation of the charcoal stratigraphy in the long core with that in the $^{209}$Pb-dated short core (Wick, 1996). Extrapolation from a radiocarbon date near the base of the core (260.5 cm) suggested an estimated age of 15 217 cal. yr BP for the beginning of the record. The age–depth curve (Figure 2) indicates slow sedimentation (approximately 0.0112 cm/yr) during the period from c. 15 000 to 7000 cal. yr BP, and faster sedimentation in the last 7000 years (approximately 0.025 cm/yr) (Table 2). The nearly linear age–depth relationship through each of these two depositional phases allowed us to use linear interpolation for the development of our age–depth model.

The lowest unit of the core (267–263 cm depth, 15 217–14 900 cal. yr BP) consists of a light grey clay, which grades into a dark olive grey clay/silt through 231 cm (11 900 cal. yr BP). The low organic content and high magnetic susceptibility of these units (Figure 3) suggest a sedimentary regime dominated by the deposition of inorganic, glacially derived sediments in a sparsely vegetated landscape.

From 231 to 184 cm depth (11 900–7600 cal. yr BP), the core consists of an olive sandy matrix with darker layers, grading into a darker olive silt above. The organic content of the sediments increases from 15% to almost 30%, consistent with the onset of forest development in the watershed and a more productive lake. Magnetic susceptibility reaches its highest values in this unit, with a large peak from 230 to 222 cm (associated with an influx of coarse sand, possibly resulting from a rapid sedimentary event), and then declines gradually to

...
near modern levels, which probably reflects increasing vegetation cover in the basin, more stable slopes and more production within the lake.

From 184 cm to the core top (7600 cal. yr BP to present), the sediments consist of an olive gyttja with abundant organic detritus, reflecting a sedimentation regime increasingly dominated by organic processes. The organic content of the sediments rises steadily to 42% at the top of the core, and the magnetic susceptibility remains low throughout the unit, except for a spike at 27–30 cm, which corresponds with a volcanic ash layer around the same depth. This layer has been found in cores from nearby lakes (Mohr et al., 2000), and is attributed to the 986 ± 200 cal. yr BP eruption of Little Glass Mountain (Heiken, 1978), approximately 80 km to the northeast (Donnelly-Nolan et al., 1990).

**Vegetation history**

The pollen record from Mumbo Lake is dominated by undifferentiated *Pinus*, which constitutes 65–85% of terrestrial pollen at all levels. Based upon changes in other abundant pollen types, the pollen record is divided into four zones (Figure 4). Plant macrofossils found throughout the core provide supplementary information about the local vegetation (Figure 5).

Zone ML-1 (267–234 cm depth, 15 217–12 100 cal. yr BP)

Zone ML-1 is distinguished by relatively high levels of Cupressaceae (0.3–16.2%), *Artemisia* (sagebrush, 3.2–10.7%), *Tsuga mertensiana* (1.4–2.4%) and diploxylen pine (0–0.9%). Macrofossils of *Pinus contorta* were found near the base of this zone. Lodgepole pine is a rapid colonizer on well-drained and poorly developed soils (Lotan and Critchfield, 1990), and may have persisted in unglaciated interfluves and basins during glacial periods. Mountain hemlock may also have been present in the basin early on, as percentages of at least 1% in the Klamath and Cascade Mountains today indicate the local presence of the tree (Minckley and Whitlock, 2000).

The pollen spectra are similar to those for open subalpine forests in the Klamath and Cascade ranges today (Heusser, 1983; Minckley and Whitlock, 2000). Cupressaceae and *Artemisia* pollen likely reflect a broad *Juniperus communis* (Ferlatte, 1974) and *Artemisia tridentata* shrub community between scattered individuals of *Pinus contorta*. Relatively high levels (up to 3.1%) of Cyperaceae, Poaceae, Apiaceae and *Salix* types indicate moist areas near the lake margin. Cold, relatively dry climatic conditions are inferred by the high percentages of *Artemisia* pollen. Charcoal analysis shows generally low background CHAR averaging 0.005 particles/cm² per yr (indicating a relatively small amount of biomass, or fuel in the basin) and low fire frequency, with an average of about 3.3 fire events per 1000 years (Figure 3).

Zone ML-2 (234–209 cm depth, 12 100–9800 cal. yr BP)

Zone ML-2 shows a decline in the percentages of *Tsuga mertensiana* (0–0.6%), *Poaceae* (0.3–0.7%), and *Apiaceae* (0–0.7%), while *Salix* and *Cyperaceae* disappear entirely. Cupressaceae (0.9–7.0%) and *Alnus* (0.7–5.4%) types peak in this zone, and *Quercus* and Rosaceae begin to increase (up to 6.6% for evergreen oaks). By c. 11 400 cal. yr BP needles

### Table 1 Radiocarbon dates from University of Arizona’s AMS facility for Mumbo Lake samples

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Material dated</th>
<th>Lab. number</th>
<th>Uncalibrated date ((^{14}C \text{ yr BP}))</th>
<th>Calibrated date ((\text{cal. yr BP})^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51.5</td>
<td>pine needles</td>
<td>AA38221</td>
<td>1925 ± 75</td>
<td>1883 ± 65</td>
</tr>
<tr>
<td>133.5</td>
<td>pine needles</td>
<td>AA33507</td>
<td>4670 ± 55</td>
<td>5441 ± 125</td>
</tr>
<tr>
<td>174.5</td>
<td>pine needles</td>
<td>AA38222</td>
<td>6085 ± 56</td>
<td>6971 ± 164</td>
</tr>
<tr>
<td>207.5</td>
<td>pine needles</td>
<td>AA38223</td>
<td>8692 ± 69</td>
<td>9717 ± 168</td>
</tr>
<tr>
<td>260.5</td>
<td>wood fragments</td>
<td>AA33508</td>
<td>12 210 ±100</td>
<td>14 658 ± 564</td>
</tr>
</tbody>
</table>

^aBased on Stuiver and Reimer (1993).

### Table 2 Sedimentation rates and deposition times for Mumbo Lake, calculated by linear interpolation between the five radiocarbon dates (and one tephra date*) for the core

<table>
<thead>
<tr>
<th>Depth range (cm)</th>
<th>Sedimentation rate (cm/yr)</th>
<th>Deposition time (yr/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0–28.5*</td>
<td>0.0297</td>
<td>33.72</td>
</tr>
<tr>
<td>28.5–51.5</td>
<td>0.0256</td>
<td>39.00</td>
</tr>
<tr>
<td>51.5–133.5</td>
<td>0.0230</td>
<td>43.39</td>
</tr>
<tr>
<td>133.5–174.5</td>
<td>0.0268</td>
<td>37.32</td>
</tr>
<tr>
<td>174.5–207.5</td>
<td>0.0120</td>
<td>83.21</td>
</tr>
<tr>
<td>207.5–260.5</td>
<td>0.0108</td>
<td>92.44</td>
</tr>
</tbody>
</table>

**Figure 2** Age–depth curve for Mumbo Lake. Notice the two-phase depositional history, with slower deposition for the first c. 8000 years of the record, then faster deposition to the top of the core.
of *Pinus jeffreyi*, *P. balfouriana* (foxtail pine), *P. contorta* and *P. monticola* are found in the macrofossil record.

The pollen spectra closely resemble those from montane forests in the Klamath and Cascade ranges today (Heusser, 1983; Minckley and Whitlock, 2000), and imply a more closed forest than before. The macrofossil assemblage indicates an increasingly diverse forest, with trees likely growing to the water's edge. Conifers and shrubs such as *Quercus vaccinifolia*, *Amelanchier utahensis* or *Spiraea douglasii* may have grown in a mosaic of forest and montane chaparral communities similar to that seen in the basin today. A peak in *Isoetes* (a submerged aquatic pteridophyte) indicates an expanded littoral zone, which may explain the decline in Cyperaceae, Apiaceae and *Salix*, as the lake expanded and flooded the surrounding flatter lakeside habitats. Somewhat warmer and effectively wetter climatic conditions are inferred by the decrease in *Artemisia* and the increase in *Alnus*, as well as the apparent expansion of the lake surface. The charcoal record shows an increase in

Figure 3 Lithology, sedimentary and charcoal indices, and inferred fire events ('peaks') and event frequencies from the Mumbo Lake record

Figure 4 Pollen percentages from Mumbo Lake. 10 × exaggeration on rare types (shaded surfaces)
background CHAR (to an average of 0.013 particles/cm² per yr) and a continued low fire frequency (3.3 events per 1000 years). The data imply effectively wetter conditions leading to more burnable biomass, but relatively few fires.

Zone ML-3 (209–96 cm depth, 9800–3800 cal. yr BP)
Zone ML-3 records the initiation of Holocene climatic conditions, and the development of the modern flora around the lake. The pollen and macrofossil records exhibit marked differences between the earlier and later portions of the zone, however, and therefore it has been broken into two subzones as below.

Subzone ML-3a (209–177 cm depth, 9800–7200 cal. yr BP)
Subzone ML-3a features increasing percentages of Quercus and Rosaceae pollen (up to 11.5% for the evergreen Quercus species), and a decrease in Abies (to a low of 0.3%), while Tsuga mertensiana pollen disappears through the middle of the subzone. Cupressaceae pollen percentages remain relatively high (0.9–3.2%), but in this case the source may be Calocedrus decurrens (incense cedar), a species more common today at lower altitudes and drier settings in the Klamath region (Table 3; note also in Figure 5 that a C. decurrens twig fragment was found in the macrofossil record for this subzone). Pinus contorta macrofossils are present through the subzone, although missing from 200 to 180 cm depth, a timespan of about 1500 years in the middle of the subzone. Pinus monticola needles are not found in subzone ML-3a, but P. jeffreyi and P. balfouriana are present up to 197 and 206 cm depth, respectively, or up to 1000 years into the subzone for P. jeffreyi. For the last 1500 years of subzone ML-3a time, few macrofossils were recovered.

Pollen assemblages resemble those from mixed conifer or mixed evergreen communities in modern Klamath and Cascade forests (Heusser, 1983; Minckley and Whitlock, 2000), suggesting a shift from the previous zone towards lower elevational communities. The decline in Isoetes implies shrinkage of the littoral zone, with the lake contracting somewhat. The occurrence of the shallow-water emergent Typha (cattail) in the latter half of the subzone may indicate the presence of marshy, seasonally flooded areas around the perimeter of the lake. Warmer and drier climatic conditions are inferred.

The trends in fire history for ML-3a actually began much earlier. Background CHAR is relatively high (averaging 0.016 particles/cm² per yr) from c. 11 700 to 8500 cal. yr BP, coincident with the strong representation of conifer needles in the macrofossil record and relatively low fire frequencies (3.3 events per 1000 years). A sharp decrease in background CHAR (to 0.002 particles/cm² per yr) at c. 8500 cal. yr BP coincides with a dearth of species in the macrofossil record and an increase in fire frequency (3.9 events per 1000 years). These shifts in the charcoal and macrofossil data may represent the transition from a mosaic of conifer forest and chaparral stands with infrequent fires to more contiguous chaparral vegetation with frequent fires, along with the warmer and drier climate.

Subzone ML-3b (177–96 cm depth, 7200–3800 cal. yr BP)
Subzone ML-3b records a rise in Abies (up to 2.6%) and Tsuga mertensiana (up to 1.9%) pollen percentages from their minima in the early Holocene. Quercus and Rosaceae pollen remain high throughout the subzone (with evergreen oaks reaching a maximum of over 14%). The macrofossil record includes essentially all the species in the modern watershed (Pinus contorta, P. monticola, P. lambertiana, Abies concolor and A. magnifica), as well as P. jeffreyi and P. balfouriana, which currently grow primarily at higher elevations.

Pollen assemblages from this zone resemble montane forests in the Klamath and Cascade ranges today (Heusser, 1983; Minckley and Whitlock, 2000), implying an expansion of forest cover into areas that previously supported chaparral, with forest stands increasing in size and density, as well as in species richness. The aquatic pollen record shows Isoetes rising throughout the zone, implying an expanded littoral habitat. Cyperaceae pollen increase and maintain a strong presence throughout this zone as well, possibly representing sedge communities in the moist forest adjacent to the lake. A shift to cooler and moister climatic conditions is inferred from the changing terrestrial and aquatic pollen records, as well as the macrofossil record.

Background CHAR rises through this subzone (averaging 0.111 particles/cm² per yr), indicating increased fuel biomass. Fire frequency also rises, averaging 5.1 events per 1000 years.

Table 3 Expected elevational ranges of tree species mentioned in the text

<table>
<thead>
<tr>
<th>Species</th>
<th>Elevation range (m)</th>
</tr>
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<tbody>
<tr>
<td>Abies concolor</td>
<td>1525–1830</td>
</tr>
<tr>
<td>Abies magnifica var. shastensis</td>
<td>1830–2590</td>
</tr>
<tr>
<td>Calocedrus decurrens</td>
<td>1525–1830</td>
</tr>
<tr>
<td>Pinus albicaris</td>
<td>2440–2740</td>
</tr>
<tr>
<td>Pinus balfouriana ssp. balfouriana</td>
<td>1830–2440</td>
</tr>
<tr>
<td>Pinus contorta ssp. murrayana</td>
<td>1525–2285</td>
</tr>
<tr>
<td>Pinus jeffreyi</td>
<td>1675–2440</td>
</tr>
<tr>
<td>Pinus lambertiana</td>
<td>1525–1830</td>
</tr>
<tr>
<td>Pinus monticola</td>
<td>1830–2135</td>
</tr>
<tr>
<td>Pseudotsuga menziesii</td>
<td>1525–1830</td>
</tr>
<tr>
<td>Tsuga mertensiana</td>
<td>1980–2590</td>
</tr>
</tbody>
</table>

From Ferlatte (1974).
One might expect fire frequency to drop somewhat from the previous subzone with the shift towards a wetter climate and more forest cover, and changes in sedimentation rates at 7000 cal. yr BP may complicate interpretation of fire event frequencies. Prior to 7000 cal. yr B.P., the sedimentation rate in Mumbo Basin was low, with each centimetre of sediment representing an average of 90 years (Table 2). After 7000 cal. yr BP the sedimentation rate increased more than twofold, and each centimetre of sediment represents an average of only 34 years. Since charcoal for the fire history analysis was sampled from contiguous 1-cm increments throughout the core, samples from the lower portion more likely contain charcoal from several fires (the current fire return interval, calculated from fire scars in the basin, is approximately 44 years (C. Skinner, unpublished data, 1996; see Whitlock et al., 2004)) than samples from the upper portion. Without finer-resolution sampling of the Mumbo Lake core, it is impossible to determine how many fires are represented in each centimetre of sediment, but it is probable that the fire frequencies over the lower half of the core are higher than those shown in Figure 3.

Zone ML-4 (96 – 0 cm depth, 3800 – 25 cal. yr BP)
Zone ML-4 records a continuation of the trends seen in subzone ML-3b, with mesic conifers such as haploxylon pines, Abies and Tsuga mertensiana continuing to increase in the pollen record, attaining maximum values of 4.6, 6.1 and 3.1%, respectively. Pollen of chaparral species, including evergreen oaks and Rosaceae, decrease through the zone to 2.7 and 1.4%, respectively. The macrofossil record contains all the conifer species from the previous zones, as well as two previously unrecorded species (Pinus albicaulis and Tsuga mertensiana).

The pollen spectra from this zone resemble upper montane or subalpine forests in the modern Klamath and Cascade ranges (Heusser, 1983; Minckley and Whitlock, 2000). Intensification of the cooling trend begun in subzone ML-3b is inferred. The charcoal record for the zone also shows a continuation of the trends seen in subzone ML-3b, with background CHAR continuing to rise (averaging 0.263 particles/cm² per yr) and fire event frequency averaging 5.0 events/1000 years.

**Discussion**
The records from Mumbo Lake and other sites (Figure 1) can be used to reconstruct the regional vegetation and fire histories (Figure 6), building on previous comparisons by West (1989) and Mohr et al. (2000). The regional comparison includes three additional records from the eastern Klamath region (Cedar Lake, West, (1989); Bluff Lake and Crater Lake, Mohr et al., (2000)); the central California coast (Coast Trail Pond, Rypins et al., (1989)); the interior Northern Coast Range of California (Clear Lake, Adam, (1988); Adam and West, (1983)); the Sierra Nevada (Swamp Lake, Smith and Anderson, (1992)); and the Oregon Coast Range (Little Lake, Worona and Whitlock, (1995); Long et al., (1998)). Though these sites span a broad elevational and latitudinal range, they are all subject to large-scale variations in climate brought about by changes in Earth’s orbital parameters (Berger, 1978; Kutzbach and Guetter, 1986; COHMAP members, 1988), and should show broadly similar trends over time.

**Late Pleistocene – early Holocene (> 11 000 cal. yr BP)**
Cooler-than-present climates are recorded for the Late Pleistocene at all sites (Figure 6). In the earliest portion of the period (> 13 000 cal. yr BP), the basins around Mumbo and Bluff lakes supported open, subalpine parkland vegetation indicating a very cold climatic regime with less available moisture than today. Swamp Lake and Little Lake both

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<tr>
<td>1000</td>
<td>Cool &amp; Moist</td>
<td>Cool &amp; Wet</td>
<td>Cool &amp; Moist</td>
<td>Cool &amp; Wet</td>
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**Figure 6** Comparison of climate reconstructions from seven palaeoecologic sites around northern California and Oregon. Climate conditions in each zone are described relative to the previous zone.
document early periods with dry alpine tundra or subalpine parkland prior to c. 16 200 and 15 400 cal. yr BP, respectively. Mumbo, Bluff and Swamp lakes show relatively low levels of charcoal during this period, which probably reflects the generally sparse vegetation and low fire activity.

By c. 13 000 cal. yr BP all of the records show a shift to more forested vegetation representative of warmer (though still cooler than present) and effectively wetter conditions. The vegetation at Mumbo, Bluff and Cedar lakes was still relatively open compared with present-day forests, whereas the Swamp Lake region supported a closed forest that was more diverse than today. The record from Coast Trail Pond at Point Reyes indicates the presence of a closed forest dominated by *Pseudotsuga menziesii* and *Abies*, in a locality which today supports only coastal scrub vegetation. The Clear Lake record, too, shows a closed forest dominated by *Pinus* and members of the T-C-T (Taxodiaceae, Cupressaceae and Taxaceae) pollen group, which probably includes *Calocedrus, Cupressus* (cypress), and *Juniperus* (Adam, 1988). Little Lake, in the Oregon Coast Range, was surrounded by a closed forest of *Pinus, Abies, Tsuga heterophylla* (western hemlock) and *Pseudotsuga menziesii*. The three lakes with charcoal data for the period (Mumbo, Bluff and Swamp) show rising but still lower than present concentrations or background CHARs. This was a period of forest development, where relative openness probably did not support widespread fires.

### Early Holocene (c. 11,000–7000 cal. yr BP)

Vegetation at all sites changed dramatically between 11 000 and 10 000 cal. yr BP, suggesting a shift to warmer and/or drier climatic conditions than before or at present. Records from the Klamath region and the Sierra Nevada suggest an open forest, or a forest mosaic with large tracts of montane chaparral (represented by increased percentages of Cupressaceae, *Quercus* and Rosaceae pollen) between smaller forest stands. At the lower-elevation California sites, Clear Lake and Coast Trail Pond, coniferous forest was replaced by open woodlands dominated by *Quercus* and xeric herbaceous taxa, or coastal sage scrub. Forest composition at Little Lake shifted from one dominated by *Abies* and *Tsuga heterophylla* to one with *Pseudotsuga menziesii, Alnus rubra* (red alder) and *Thuja plicata* as the primary tree species. Both *P. menziesii* and *A. rubra* are often associated with warmer, drier conditions and higher fire frequencies in the early Holocene (Long *et al.*, 1998). At Mumbo, Bluff and Swamp lakes, concentration and background CHAR values increase from c. 11 000 to 7000 cal. yr BP. The open forest/chaparral assemblages seen in the Klamath and Sierra Nevada sites likely supported less biomass than dense forests at any given time, but they may have burned more frequently. Mumbo and Bluff lakes show peaks in fire frequency during this period, as do Little and Crater lakes where their records cover the period.

### Middle to late Holocene (c. 7000 cal. yr BP to present)

The forest composition changed at c. 7200 cal. yr BP at Mumbo Lake, suggesting a gradual return to cooler, moister conditions. Other records show similar changes between about 8400 and 6600 cal. yr BP. For example, at Cedar and Swamp lakes a decline in chaparral types and an increase in arboreal taxa such as *Pinus* and *Cupressaceae* suggest a shift towards cooler and moister conditions. *Abies* expanded at Bluff and Crater lakes about this time, though as at Mumbo Lake chaparral types maintained a strong presence in these records for some time afterwards. At Little Lake, *Tsuga heterophylla* increased as *Pseudotsuga menziesii* decreased somewhat, indicating the return to a more mesic forest environment.

This climatic transition is not as clear at the lowland California sites. At Coast Trail Pond, terrestrial pollen percentages remained unchanged throughout the Holocene. The increasing proximity of the ocean as sea levels rose after deglaciation may have muted the effects of any potential climate changes at the site by diminishing diurnal and annual temperature fluctuations. At Clear Lake, pollen percentages also change little throughout the Holocene, but *Quercus* percentages decrease slightly around 6000 cal. yr BP and those of both *Pinus* and T-C-T increase. The temperature reconstructions (Adam and West, 1983), calibrated here for calendar years, show a peak in temperature during the early Holocene, followed by a gradual cooling.

The charcoal records from Mumbo, Bluff, Little and Swamp lakes show gradually increasing concentrations or background CHARs throughout the middle to late Holocene, indicating an increase in fuel biomass as the forests became more dense and productive. This was also noted in a study from meadow sediments in the Sierra Nevada (Anderson and Smith, 1997), and to a lesser extent at Siesta Lake in Yosemite National Park (Brunelle and Anderson, 2003). At Mumbo, Bluff, Crater and Little lakes, the number of fire events per 1000 years fluctuated throughout this period, with generally lower frequencies than during previous periods. All four records show a moderate to dramatic peak in fire frequency around 1000 cal. yr BP, which may be ascribed to climatic conditions during the 'Medieval Warm Period' (Mohr *et al.*, 2000; Brunelle and Anderson, 2003).

At Mumbo Lake, changes in the pollen record (including an increase in *Abies, Tsuga* and haploxylon *Pinus*, and a decrease in evergreen *Quercus*) suggest an intensification of the cooling trend at about 3800 cal. yr BP. In several of the other records distinct changes are noted at about this time, which also imply cooler, possibly wetter climates, tentatively attributed to the effects of Neoglacialion (Anderson, 1990; Smith and Anderson, 1992). At Bluff and Swamp lakes, *Abies* becomes more important in the pollen record around 4000 cal. yr BP, indicating moister conditions. At Cedar Lake increases in *Pseudotsuga menziesii, Abies* and Ericaceae in this time period indicate a similar trend towards a more moist, closed forest, while at Little Lake this change is heralded by the increasing importance of *Tsuga heterophylla* in the pollen record.

### Conclusions

The climatic reconstruction from Mumbo Lake correlates well with other palaeoecological records from northern California and the Pacific Northwest, indicating that similar broad-scale climate changes have influenced vegetation throughout this region over at least the past 15 000 years. The overall picture of (1) a cool, dry period immediately after deglaciation, followed by (2) still cool but increasingly moist climates up to the Pleistocene/Holocene transition around 11 000 cal. yr BP, succeeded by (3) with a warmer and drier early Holocene and (4) a return to cooler and moister climates in the middle to late Holocene also validates the results of climate model simulations that portray the effects of variations in glacial ice and the Earth's orbital parameters (Kutzbach and Guetter, 1986; Thompson *et al.*, 1993; Bartlein *et al.*, 1998). The fact that our Mumbo Lake fire history is in broad agreement with that of other Klamath lakes (Mohr *et al.*, 2000) suggests that climate has been a dominant factor in determining regional burning as well. This is particularly true for c. 1000 cal. BP.
Elevated fire frequency has been shown not only for the Klamath Mountains, but also for the Sierra Nevada (Brunelle and Anderson, 2003), the Coast Range (Long et al., 1998) and some sites in the northern Rockies (Whitlock et al., 2003).

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