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Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA

Jerry A. Mohr,[1] Cathy Whitlock[1] and Carl N. Skinner[2]

([1]Department of Geography, University of Oregon, Eugene, Oregon 97403, USA; [2]US Forest Service, Pacific Southwest Research Station, Redding, California 96001, USA)

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Abstract: Pollen and high-resolution charcoal data from Bluff Lake and Crater Lake, California, indicate similar changes in climate, vegetation and fire history during the last 15 500 years. Pollen data at Bluff Lake suggest that the vegetation between *c.* 15 500 and 13 100 cal. BP consisted of subalpine parkland with scattered *Pinus* and *Abies*. After 13 100 cal. BP a relatively closed forest of *P. monticola*, *P. contorta* and *Abies* developed, and fire-event frequency was low. The inferred climate then was cooler and wetter than present. *Pinus* and *Quercus vaccinifolia* dominated at both sites during the early Holocene, when conditions were warm and dry. As climate became wetter and cooler in the late Holocene, *Abies* spp. at both sites and *Tsuga mertensiana* at Crater Lake increased in importance, displacing *Pinus* and *Quercus*. The two lake records have similar trends in fire history, with high event frequencies at *c.* 8400, 4000 and 1000 cal. BP and low values at *c.* 4800 cal. BP. The fire and vegetation history at both sites suggests a similar response to large-scale changes in climate during the Holocene.

Key words: Fire history, vegetation history, charcoal records, Holocene, Pacific Northwest, Klamath Mountains.

Introduction

The alpine, subalpine and montane forests of the Klamath Mountain region of northern California are noted for their high floristic diversity (Whittaker, 1960). The unique mixture of taxa from the Pacific Northwest, California, and Great Basin contribute to the complexity of the vegetational patterns (Sawyer and Thornburgh, 1988). The floristic diversity found in the Klamath Mountains results from the combination of varied parent material and elevational and climatic gradients that has created a diversity of habitats (Whittaker, 1960). *Pinus balfouriana* (foxtail pine), *Abies lasiocarpa* (subalpine fir) and *Chamaecyparis lawsoniana* (Port Orford cedar) occur in widely scattered stands at the geographic limit of their ranges here (common names are based on nomenclature from Hickman, 1993, and Munz, 1973). These forests also contain many endemic species (e.g., *Picea breweriana*, Brewer spruce) and the highest percentages of relict species in California (Whittaker, 1961; Raven, 1988).

Fire has also played a significant role in structuring the present-day montane forests of the Klamath Mountains. Fire histories in this region have been based on dendrochronologic records (Agee, 1991; Wills and Stuart, 1994; Taylor and Skinner, 1998), but the length of record is limited to fire scars on stumps, logs and living trees. Fires in the Klamath Mountains are more frequent and less severe than in the Pacific Northwest but less frequent than in the central Sierra Nevada (Sawyer and Thornburgh, 1988). Dendrochronologic studies indicate that fires are frequent and occasionally large but are generally low- or moderate-intensity surface events (Skinner and Chang, 1996). Studies of long-term fire and vegetation history have not been undertaken in the Klamath Mountains.

To understand the Holocene vegetation and fire history better, we examined two sites on opposite sides of a major east–west-trending divide and thus in contrasting environments. Bluff Lake (41°20′N, 122°33′W, 1921 m, water depth 1.70 m) lies in a southeast-facing valley on the south side of South China Mountain (Figure 1). Crater Lake (41°24′N, 122°35′W, 2288 m, water depth 12.15 m) lies behind a glacial moraine on the northwest-facing slope of China Mountain (Figure 1). Comparison of two sites in close proximity but at different elevations and topographic settings made it possible to assess the spatial variability of the local vegetation and fire history in response to regional climatic changes.

Setting

Bluff Lake is located in open forest composed of *Pinus jeffreyi* (jeffrey pine), *P. contorta* (lodgepole pine), *P. monticola* (western

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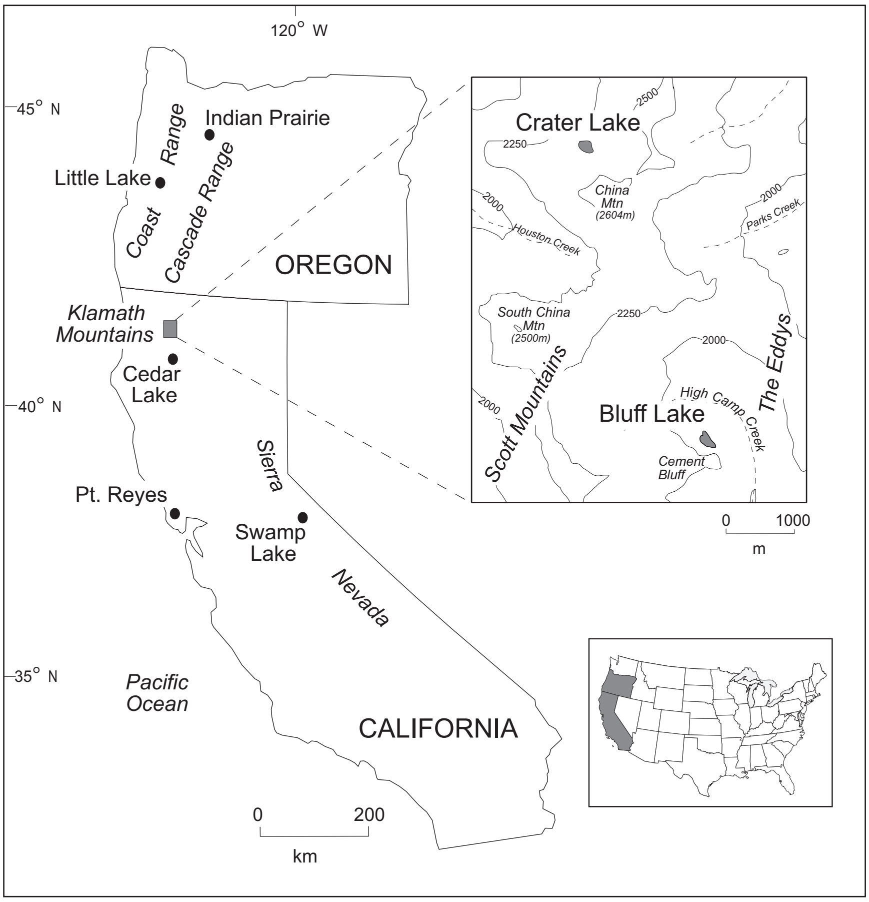

Figure 1 Map showing the location of Bluff Lake, Crater Lake and other sites discussed in text.

white pine), *Abies concolor* (white fir), *Calocedrus decurrens* (incense cedar) and *Pseudotsuga menziesii* (Douglas fir). *Pinus lambertiana* (sugar pine) grows at elevations below the lake, while *P. attenuata* (knobcone pine) can be found on nearby ridges. Understorey shrubs include *Quercus vaccinifolia* (huckleberry oak), *Ceanothus prostratus* (mahala mat), *Arctostaphylos patula* (green leaf manzanita) and *A. nevadensis* (pinemat manzanita). The subalpine forest that surrounds Crater Lake is composed of *Pinus balfouriana*, *P. albicaulis* (whitebark pine), *P. monticola*, *P. contorta*, *Abies magnifica* (California red fir) and *Tsuga mertensiana* (mountain hemlock) (Keeler-Wolf, 1987). The understorey is dominated by *Ceanothus prostratus* and *Arctostaphylos patula*.

Most of the precipitation in the eastern Klamath region occurs in winter as snow, with occasional thunderstorms in summer. Records at the Mt Shasta Weather Bureau Station (elevation 1080 m), approximately 20 km to the southeast, show a mean annual precipitation of 96.5 cm. The mean daily temperature ranges from –3.6°C in January to 29.3°C in July at the Mt Shasta station. Bluff and Crater lakes are located at higher elevations, and the climate is correspondingly cooler and wetter.

The lakes lie on the Trinity Ultramafic sheet (Trinity Pluton), which is the oldest and largest single ultramafic exposure in western North America (Irwin, 1981). The Trinity peridotite parent rock is variably serpentinized in areas adjacent to Bluff and Crater Lakes. Evidence of past glaciation on nearby Mt Eddy, Cedar Basin and the Trinity Alps (Whipple and Cope, 1979; Keeler-Wolf, 1987; Sharp, 1960) suggests a late-Pleistocene snow-line depression of *c*. 300 m. Both Bluff and Crater Lakes are dammed by moraines, presumably of late-Pleistocene age.

The vegetation in the eastern Klamath Mountains reflects gradients in temperature and precipitation (Table 1) and the character of the ultramafic bedrock. The Scott River valley at low elevations (*c*. 900 m elevation northwest of Crater Lake) supports an open *Pinus ponderosa* (ponderosa pine)-*Juniperus*-*Quercus* forest. At higher elevations *P. ponderosa* and *Quercus garryana* (Oregon white oak) occur on the steep dry hillsides. The lower montane forest (1300 to 1600 m elevation) is dominated by *P. ponderosa*, *P. lambertiana* and *Abies concolor*, with minor components of *Pseudotsuga menziesii* and *Calocedrus decurrens*. *Pinus jeffreyi* replaces *P. ponderosa* locally where soil conditions are poor due to serpentinization. Upper montane forests (1400 to 1950 m elevation) on mesic sites consist of open mixed stands over a continuous layer of sclerophyllous shrubs. At higher elevations (1900 to 2200 m) and on more xeric sites, open woodlands lack a continuous shrub understorey. *Tsuga mertensiana*, *Pinus baulforiana*, *P. albicaulis* and *Abies magnifica* dominate subalpine forests. The sparse shrub understorey is dominated by *Artemisia tridentata* (big sagebrush), *Cercocarpus ledifolius* (mountain mahogany) and *Arctostaphylos* spp. (Whipple and Cope, 1979; Keeler-Wolf, 1987).

Methods

Field

Long sediment cores were collected using a 5 cm diameter modified Livingstone square-rod piston sampler (Wright *et al*., 1983) from an anchored platform located in the deepest water at both sites. Cores were extruded in the field, wrapped in cellophane and aluminum foil, and stored under refrigeration. In addition, a short core 52 cm long was retrieved by use of a 5 cm diameter plastic tube fitted with a piston and operated by rigid drive rods. A short core taken at Bluff Lake to recover the mud-water interface was used to study the last 200 years in detail. Cores were extruded vertically from the top of the tube at 0.5 cm intervals for the upper

Table 1 Modern vegetation zones, eastern subregion Klamath Mountains, California (from Sawyer and Thornburgh, 1988; Vasek and Thorne, 1988)

Elevation range (m)	Generalized vegetation zones	Characteristic species
900–1300	*Pinus ponderosa*	*Pinus ponderosa* *Pinus jeffreyi*[a] *Juniperus occidentalis* *Quercus garryana* *Purshia tridentata* *Ceanothus cuneatus*
1300–1600	*Abies concolor*	*Abies concolor* *Pinus ponderosa* *Pinus jeffreyi*[a] *Pinus lambertiana* *Pseudotsuga menziesii* *Calocedrus decurrens*
1400–1950	*Abies magnifica*	*Abies magnifica* *Abies concolor* *Pseudotsuga menziesii* *Pinus monticola* *Picea breweriana* *Pinus lambertiana* *Pinus jeffreyi*[a] *Calocedrus decurrens* *Pinus contorta* *Quercus vaccinifolia* *Arctostaphylos patula*
1900–2200	*Tsuga mertensiana*	*Tsuga mertensiana* *Abies magnifica* *Pinus balfouriana* *Pinus albicaulis* *Pinus contorta* *Pinus jeffreyi*[a] *Pinus monticola* *Quercus vaccinifolia* *Pyrola picta* *Holodiscus micropyllus* *Phyllodoce empetriformis*
>2200 (>2700[b])	*Pinus albicaulis*	*Pinus albicaulis* *Cercocarpus ledifolius* *Holodiscus microphyllus* *Potentilla glandulosa*[b] *Penstemon procerus*[b]

[a] On ultrabasic parent material.
[b] On Mt Eddy.

10 cm and at 1 cm intervals to a depth of 40 cm. Subsamples were stored in plastic bags and refrigerated when returned to the laboratory.

Laboratory

Individual core segments were sliced longitudinally for description of the lithology. Samples of 1 cm^3 were taken at 10 cm intervals for loss-on-ignition analysis. Samples were dried 24 hours at 90°C. Weight loss after burning the samples for two hours at 550°C was used to calculate the percent of organic content, and weight loss after two hours at 900°C was used to determine carbonate percentages (Dean, 1974).

Sediment magnetic susceptibility was measured for each 1 cm interval from the Bluff and Crater lake cores. Subsamples of 8 cm^3 for each interval were put into a plastic cup and placed in a cup-coil magnetic-susceptibility instrument made by Sapphire Instruments.

Charcoal analysis was performed at contiguous 1 cm intervals for the entire length of both long cores, and at 0.5 cm intervals for the upper 10 cm and at 1 cm intervals to a depth of 40 cm from the Bluff Lake short core. From each interval, 5 cm^3 was subsampled and disaggregated in a 5% solution of sodium hexametaphosphate for three days. The residue was wet-sieved through a nested series of metal screens with mesh sizes of 250, 125 and 63 μm. Each sample was placed in a gridded petri dish, and the charcoal in each size class was counted under a stereomicroscope at 50× magnification. This sampling strategy was adopted from sediment charcoal studies described by Millspaugh and Whitlock (1995) and Long *et al*. (1998). Examination of the charcoal counts in the first metre showed that the different particle-size classes compared well. The smallest particle-size class (63–125 μm), however, was difficult and time-consuming to count. Whitlock and Millspaugh (1996) also found that the this size fraction conveyed the same information as the larger size classes. For this reason, only macroscopic particles >125 μm in diameter were considered in the remainder of the cores. Charcoal accumulation rates (particles cm^{-2} year^{-1}) were calculated by dividing the charcoal concentrations by the deposition time (years cm^{-1}) for each sample.

Pollen analysis was undertaken at 10 cm intervals along the length of each core to reconstruct the general features of the vegetational history. Samples were processed with standard techniques (Faegri *et al*., 1989), including addition of *Lycopodium* tracer spores for calculation of pollen concentration (grains cm^{-3}) and pollen accumulation rates (grains cm^{-2} year^{-1}). Individual pollen grains were identified to the lowest possible taxonomic level at magnifications of 500 and 1250× by comparison with the pollen and spore reference collection at the Department of Geography, University of Oregon, published atlases (Bassett *et al*., 1978; Kapp, 1969; Moore and Webb, 1978), and journal articles for specific taxa (Jarvis *et al*., 1992; Hebda *et al*., 1988a; 1988b). The assignment of particular pollen taxa was based on modern phytogeography. Diploxylon-type pine was assigned to *Pinus jeffreyi, P. ponderosa, P. attenuata* or *P. contorta*. Haploxylon-type pine contributors include *P. monticola, P. albicaulis, P. balfouriana* and *P. lambertiana*. *Pinus* grains that lacked a distal membrane were identified as undifferentiated *Pinus*. These grains were assumed to contain the same proportions of haploxylon-type and diploxylon-type as in the identified *Pinus*. *Abies* pollen grains were attributed to *A. concolor, A. magnifica, A. procera* (noble fir), *A. amabilis* (Pacific silver fir) or *A. lasiocarpa*. Cupressaceae pollen may have come from *Calocedrus decurrens, Chamaecyparis lawsoniana, Juniperus communis* (common juniper) or *J. occidentalis* (western juniper). *Chrysolepis*-type pollen was either *C. chrysophylla* (chinquapin) or *Lithocarpus densiflora* (tanbark oak), but these very small grains (*c*. 15 μm) are too similar in appearance to distinguish (Heusser, 1983). *Cercocarpus*-type pollen primarily includes *C. ledifolius* and *Purshia tridentata* (antelope bush) (Anderson and Davis, 1988). *Quercus vaccinifolia*-type pollen was distinguished from *Q. garryana*-type based on the coarseness of the sculpturing elements and differences in the apertures (Jarvis *et al*., 1992). Ericaceae pollen could be *Arctostaphylos nevadensis, A. patula, Rhododendron occidentale* (western azalea) or *Vaccinium arbuscula* (dwarf bilberry); this zoophyllus type is an important component of the modern understorey yet is rarely seen in pollen assemblages. At least 400 grains were counted exclusive of spores and aquatic pollen for each level, and most counts consisted of at least 100 non-*Pinus* grains. Pollen grains that could not be identified were counted as ‘unknown’; those grains that were broken, corroded, hidden or otherwise damaged were counted as ‘indeterminate’.

Data analysis

Chronology

Thirteen sediment samples of 0.5–1.9 g from the top 20 cm of the Bluff Lake short core were submitted for ^{210}Pb age determinations. Calendar dates for the Bluff Lake short core are shown on Figure 2A. Sediment age-versus-depth relations were based on 13 ^{210}Pb dates. The top of the core was assigned an age of AD 1995, the year the core was taken, and the chronology was extended back 200 years at 0.17 m depth.

Six macrofossil samples from Bluff Lake and five samples from Crater Lake were submitted for accelerated mass-spectrometry (AMS) dating. Uncalibrated radiocarbon dates (^{14}C yr BP), calibrated ages (cal. BP) (Stuiver and Reimer, 1993) and age-versus-depth models for both sites are listed in Table 2. The age (calendar year BP)-versus-depth curves derived from the models are plotted in Figure 2, B and C, with uncalibrated ^{14}C dates of samples shown at the corresponding depth in each core. The top of each core was assigned an age of 0 cal. BP.

Pollen

Pollen counts of all identified taxa except aquatics were included in the pollen sum and converted to percentages to suggest the relative proportions of the upland trees, shrubs, herbs and pteridophytes for each sample. Aquatic pollen counts were converted to percentages based on a sum of all pollen types. The pollen-percentage records were divided into zones by use of a constrained cluster analysis (CONISS; Grimm, 1988). Pollen concentration (grains cm^{-3}) and deposition time (year cm^{-1}) were used to calculate pollen accumulation rates (grains cm^{-2} year^{-1}) to determine changes in individual taxa abundance over the length of the record independent of other pollen types (Birks and Gordon, 1985).

Charcoal

The decomposition approach of Long *et al*. (1998) was used to separate CHAR (charcoal accumulation rate = particles cm^{-2} year^{-1}) time-series into two components: one that indicates the occurrence of a fire event and one that relates to the combined effects of sedimentation and charcoal production. Several factors determine the rate at which charcoal accumulates in lake sediments. First, standing biomass, fire severity and available fuel load determine the amount of charcoal produced during a fire. Second, the charcoal deposited in lake sediments depends on the atmospheric and fluvial processes that entrain and transport charcoal. Finally, sedimentologic processes within a lake control where and when charcoal will accumulate in the deep-water sediments (Clark and Royall, 1995; Bradbury, 1996; Whitlock and Millspaugh, 1996; Long *et al*., 1998). The CHAR time-series was therefore separated into a low-frequency or slowly varying *background* component and a higher-frequency or more rapidly varying *peaks* component, which represent these factors.

The background component is composed of a general but time-varying level of CHAR that reflects the rate of charcoal production. It also may represent charcoal that is sequestered in the watershed and in the littoral zone of the lake for long periods after the fire event and then transported and deposited in deep-water sediments. In addition, the background component may include the contribution of charcoal from non-local or regional fires. Thus, variation in the background components may reflect changes in vegetation, watershed storage and lake characteristics, as well as climatic change. The *peaks* component represents the input of charcoal from a *fire event* in the 'charcoal catchment', i.e., the watershed of the lake and/or adjacent watersheds. A second contributor to a peak is a minor 'noise' component that includes both the analytical error in CHAR determinations and random variations in CHAR (Long *et al*., 1998).

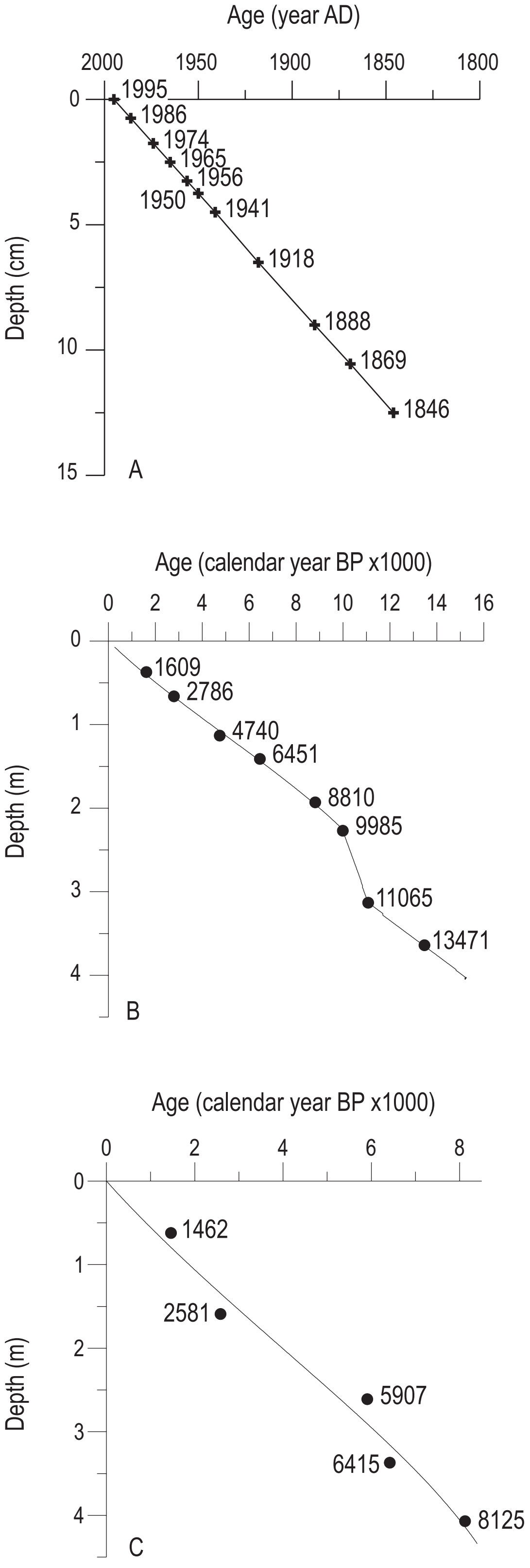

Figure 2 (A) Age-versus-depth curve for Bluff Lake short core based on a series of ^{210}Pb dates. Dates were provided by Battelle Marine Sciences Laboratory, Sequim, Washington. (B) Age (calendar year BP)-versus-depth curve for Bluff Lake. (C) Age (calendar year BP)-versus-depth curve for Crater Lake. Uncalibrated ^{14}C dates are plotted by depth. See Table 2 for age models applied to each curve.

A 'fire event' is defined in this study as one or more fires occurring within the time of a sampling interval (Long *et al*., 1998). In order to detect individual fires, the interval between fires must be longer than the sediment-sampling interval. Dendrochronologic studies at Bluff Lake indicate modern median fire-return intervals

Table 2 Uncalibrated radiocarbon dates and calibrated ages from Bluff Lake and Crater Lake

Depth (m)[a]	Uncalibrated ^{14}C age (^{14}C yr BP)	Calibrated age (cal. BP)[b]	Material dated	Lab. number
Bluff Lake				
Core 95A				
0.37	1720 ± 50	1698, (1609[d]), 1543	Conifer needles	AA20622
0.66	2720 ± 60	2861, (2786[d]), 2759	Conifer needles	AA23317
1.13	4220 ± 55	4839, (4826, 4740[d], 4738), 4648	Wood	AA20623
1.41	5675 ± 55	6497, (6451[d]), 6409	Conifer needles	AA23318
1.93	7960 ± 100	8983, (8942, 8912, 8810[d], 8795, 8720), 8564	Wood	AA22157
2.27	9025 ± 70	10 035, (9985[d]), 9955	Wood	AA20624
3.13	9940 ± 75	11 328, (11 071, 11 065[d], 11 030), 10 999	Wood	AA20625
3.71	8220 ± 120[c]	9374, (9098, 9120, 9098, 9061, 9056) 8988	Conifer needle	AA20626
Core 95C				
3.64	11 550 ± 90	13 609 (13 471[d]), 13 351	Conifer needles	AA22158
Bluff Lake age models:				
0–9985 cal. BP	$Age = -319.068*depth^3 + 1087.91*depth^2 + 3599.49*depth$	$r^2 = 0.9993$		
9985–11065 cal. BP	$Age = 1080*depth + 8905$			
11065–13471 cal. BP	$Age = 2406*depth + 8659$			
Crater Lake				
Core 96A				
0.62	1585 ± 45	1527, (1501, 1462[d], 1457), 1405	Conifer needles	AA23312
1.59	2500 ± 45	2725, (2709, 2621, 2614, 2581[d], 2541, 2533, 2509, 2357	Wood	AA23313
2.61	5130 ± 55	5930, (5907[d]), 5765	Conifer needles	AA23314
3.37	5650 ± 50	6480, (6415[d]), 6356	Wood	AA23315
4.07	7355 ± 175	8327, (8125[d]), 7940	Conifer needles	AA23316
Crater Lake age model:				
$Age = -31156*depth^4 - 19.6547*depth^3 + 198.644*depth + 1698.57*depth$		$r^2 = 0.9908$		

[a] Depth below mud surface.
[b] Based on Stuiver and Reimer (1993).
[c] Possibly contaminated, age not used in the age-versus-depth equations.
[d] Calibrated ages used in age-versus-depth equations.

of 10–12 years with a range of 3–217 years. Modern median fire-return intervals at Crater Lake are 11–14 years with a range of 2–122 years, based on dendrochronologic data within the watershed. The average sedimentation rate at Bluff Lake is *c.* 0.039 cm year^{-1}; so 1 cm spans a *c.* 39-year period and probably includes several fires. Crater Lake sedimentation averaged *c.* 0.019 cm year^{-1}; so 1 cm spans *c.* 19 years and may contain charcoal from more than one fire. Because of slow sedimentation rates the time-span of a charcoal peak or fire event ranges from 24 to 180 years at Bluff Lake and from 12 to 120 years at Crater Lake.

The CHAR time-series was produced by interpolating raw charcoal-concentration values and deposition times to pseudo-annual intervals, then converting these values to CHARs by integrating the resulting concentration values over 12-year intervals divided by the average deposition time (year cm^{-1}) . Twelve years was selected because it was the shortest deposition time in either record. Figure 3 compares the raw concentration values plotted by depth (A) and time (B) and the uninterpolated accumulation rates (C) with the accumulation rates plotted at 12-year intervals (CHARs) (D and E). This approach preserves the features of the raw charcoal-accumulation-rate stratigraphy but allows us to analyse the data at equally spaced time intervals (Long *et al.*, 1998). The background component was calculated by applying a locally weighted (moving) average to the CHAR time-series. The tricube weight function (Cleveland, 1993) was used to calculate the weights, thus giving points near the centre of the window more influence on the weighted average than points closer to the edge. A CHAR-value threshold was assigned to the peaks component (fire event) to remove the noise subcomponent. The threshold is defined as a ratio of CHAR to the background component. A fire event is identified when the peaks component exceeds the selected threshold ratio (Long *et al.*, 1998).

The selection of a threshold-ratio value was based on the dendrochronologic and documentary evidence of recent fires. Our goal was to select a value for the short core at Bluff Lake and the top of the long cores at Bluff Lake and Crater Lake that would correctly identify decades with significant burning in the last few centuries. The window-width and threshold parameters were also chosen by comparing the results of the decomposition with different values. A threshold-ratio value of 1.00 and a window width of 120 years was selected for Bluff Lake, where independent information on fires was available; these values were also applied to Crater Lake. It should be noted, however, that use of different values for background and threshold ratio did not substantially affect the fire reconstruction (Mohr, 1997). To depict the results graphically, a locally weighted mean frequency of fire events (number of fire events/number of years) was produced by smoothing the binary series of fire events (1 = fire event, 0 = no fire event).

Results

Lithology

At Bluff Lake, the lowest unit (4.22–4.31 m depth) consisted of dark greenish silty clay. Between 3.84 and 4.22 m depth the sediment consisted of dark grey inorganic silty clay; 1 cm bands of coarse sand were noted at 3.92, 4.01 and 4.11 m depth. The over-

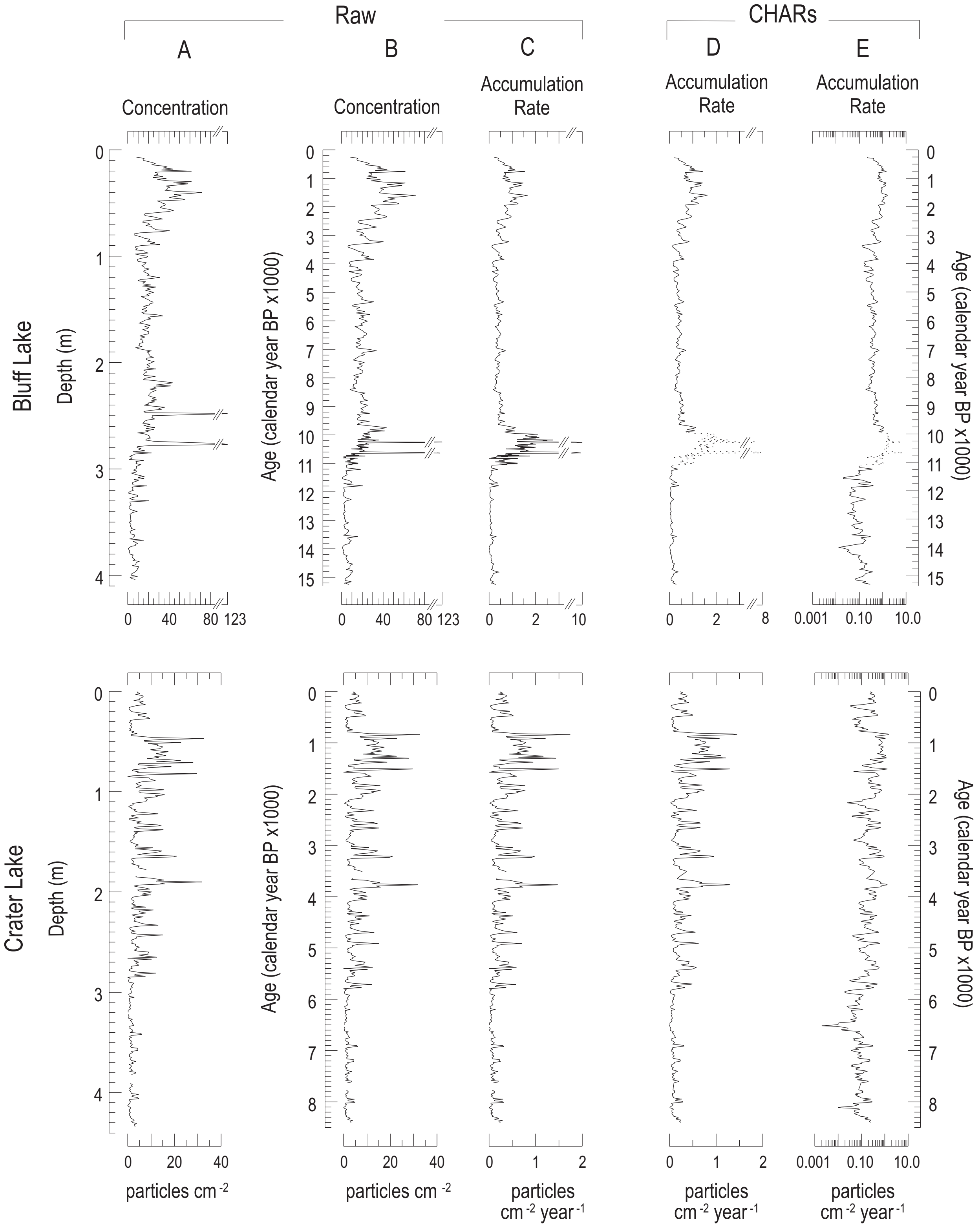

Figure 3 Charcoal concentration and accumulation rates before (A, B and C) and after decomposition (D and E) for Bluff and Crater Lakes. (A) Concentration of raw charcoal counts plotted by depth. (B) Concentration of raw charcoal counts plotted by age (cal. BP). (C) Charcoal accumulation rates (CHARs) calculated from raw charcoal concentration data. (D) Accumulation rates calculated using decomposition method of Long *et al.* 1998 (see discussion). (E) Decomposed accumulation rates plotted on a log10 scale. (Note: dashed line in the Bluff Lake record was segment in core not included in analysis.)

lying unit (2.38–3.84 m depth) was composed of dark olive grey fine-detritus gyttja. Two 2 cm thick layers of pinkish grey fine sand and silt occurred at 3.26–3.28 m and 2.92–2.94 m depth, a 1 cm thick layer of sand and silt was present at 2.86 m depth. A 5 cm thick layer of dark greyish brown coarse organic detritus occurred from 2.46 to 2.51 m depth. Overlying this layer was olive grey fine-detritus gyttja. Loss-on-ignition data indicate that the organic content of the sediment ranged from 4.7% at 2.87 m depth to 37.6% at 1.57 m depth (Figure 4). Sediment carbonate content ranged from 0.3% at 2.67 m depth and 7.3% at 2.47 m depth.

The lowest unit of the Crater Lake core (4.34–3.91 m depth) consisted of a mixture of dark olive grey fine-detritus gyttja, interspersed with dark greyish brown coarse detritus. The remaining

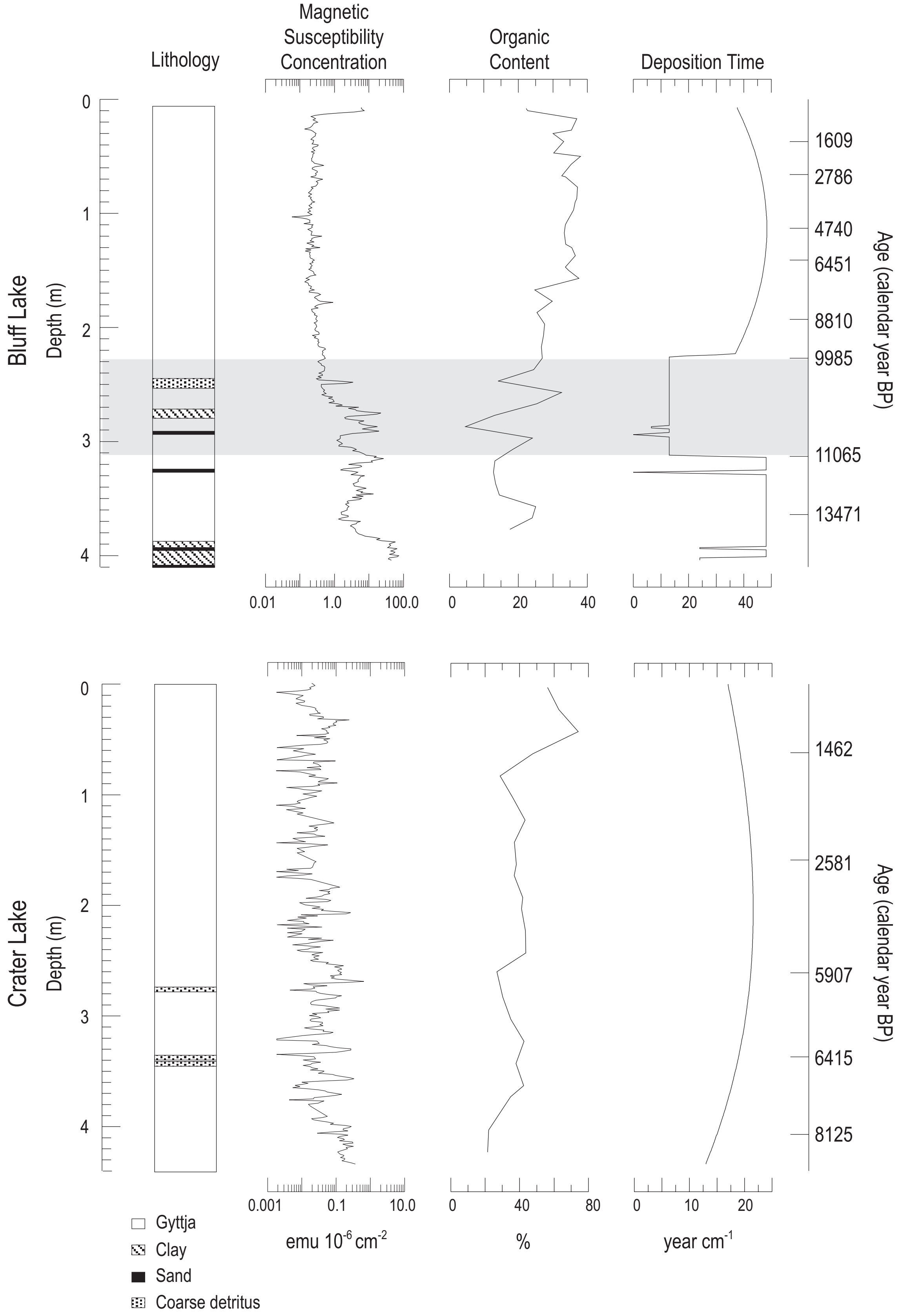

Figure 4 Lithology, magnetic susceptibility concentrations, organic content, deposition time and uncalibrated ^{14}C dates for Bluff Lake and Crater Lake. Shaded area on Bluff Lake graph shows segment of core where one or more rapid sedimentological events occurred.

sediment (3.90–0.00 m depth) was dark olive grey fine- to very fine-detritus gyttja with layers of coarse detritus at 2.76–2.74 m, 2.63–2.62 m, 3.38–3.36 m and 3.42–3.41 m depth. The organic content of Crater Lake sediment ranged from 21% at 4.23 m depth to 44% at 2.43 m depth (Figure 4). Sediment carbonate content was 0% at 2.43 m depth and reached 3% at 1.23 m depth.

Magnetic-susceptibility measurements provide a proxy-record of erosion in the watersheds (Rummery *et al.*, 1979; Millspaugh and Whitlock, 1995). Magnetic-susceptibility concentration for the Bluff Lake 95B short core was moderate to high from AD 1977 to 1995 (0.4×10^{-6} to 0.9×10^{-6} emu cm^{-1}). Rates were high to very high (1.1×10^{-6} to 2.0×10^{-6} emu cm^{-1}) from AD 1935 to

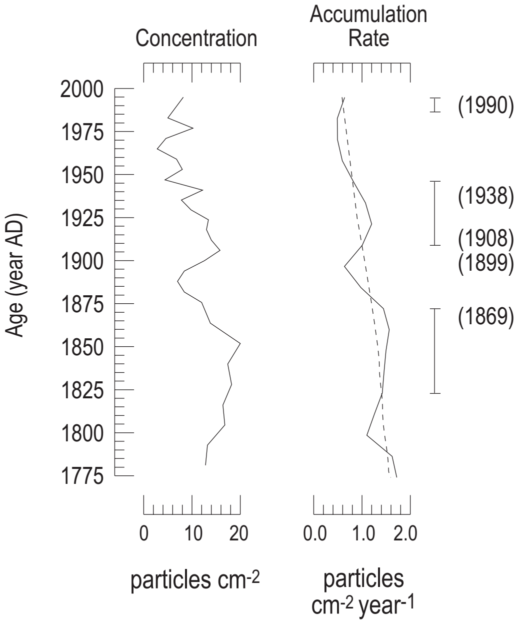

Figure 5 Charcoal concentration and CHAR (charcoal accumulation rate) for Bluff Lake for the last 200 years (solid lines). Raw data were decomposed into background component (dashed line) using the same parameters as the long record. Bars indicate fire-event intervals inferred by values above background. Numbers in ( ) are years of fire identified from dendrochronologic data.

1977, and low to moderate (0.2×10^{-6} 0.8×10^{-6} emu cm^{-1}) for the next 155 years (1780 to 1935) (Figure 5).

Bluff Lake magnetic-susceptibility long-core record shows that from *c*. 15 300 to 14 800 cal. BP magnetic susceptibility was very high (34.70×10^{-6} to 72.42×10^{-6} emu cm^{-2}). The values were moderate to very high (0.41×10^{-6} to 26.24×10^{-6} emu cm^{-2}) from *c*. 14 700 to 10 200 cal. BP. From *c*. 10 200 to 400 cal. BP the values were low to moderate (0.11×10^{-6} to 0.90×10^{-6} emu cm^{-2}). In the last 400 years, the values have been high (3.86×10^{-6} to 7.26×10^{-6} emu cm^{-2}) (Figure 4). The magnetic-susceptibilty concentration values at Crater Lake were low (0.00×10^{-6} to 0.19×10^{-6} emu cm^{-2}) from *c*. 7800 cal. BP to present, with higher values (0.26×10^{-6} to 0.64×10^{-6} emu cm^{-2}) occurring at *c*. 7180, 6700, 5450 and 4100 cal. BP. Between *c*. 8400 and 7900 cal. BP magnetic-susceptibility concentration values ranged from 0.11×10^{-6} to 0.36×10^{-6} emu cm^{-2} (Figure 4). In both these records no correlation was found between charcoal peaks and magnetic-susceptibility peaks. The lack of correspondence suggests that fire events are not associated with pulses of erosion in this region, unlike other locations (Millspaugh and Whitlock, 1995).

Pollen and charcoal records

Bluff Lake

Five zones were identified in the Bluff Lake pollen record: BL-1 (*Artemisia*-*Potentilla*-*Pinus*), BL-2 (*Pinus*), BL-3 (*Quercus*-Cupressaceae-*Pinus*), BL-4 (*Quercus*-*Pinus*-Poaceae) and BL-5 (*Abies*-*Pinus*). Zone BL-2 is further divided into two subzones: BL-2a (*Pinus*-*Abies*) and BL-2b (*Pinus*-*Cheilanthes*). The charcoal-analysis results are plotted in Figure 6, and selected taxa are plotted in Figure 7.

Zone BL-1 (>13 100 cal. BP) features high percentages of shrub and herb taxa, suggesting an open, dry environment with few trees. The low percentages of *Abies* (most likely *A. magnifica*) at the bottom of the zone indicate fir was probably absent locally. The low percentages of *Pinus* at the bottom of the zone are characteristic of modern pollen spectra for alpine regions, where the trees occur either as stunted, isolated individuals on or near the site or at lower elevations where their pollen is blown upslope (Anderson and Davis, 1988). Haploxylon-type *Pinus* pollen is probably from *P. albicaulis* and/or *P. balfouriana*. Diploxylon-type could be from *P. contorta*.

This pollen zone is similar to modern pollen spectra from alpine regions in the Trinity Alps and the central Sierra Nevada (Heusser, 1983; Anderson and Davis, 1988). The vegetation during zone BL-1 time may also have been similar to the modern vegetation at elevations above 2700 m found on nearby Mt Eddy. Here alpine shrubs and herbs dominate on open rocky slopes and meadows with occasional stunted *Pinus albicaulis* and *P. balfouriana* (Whipple and Cope, 1979). At the top of the zone *Abies* and diploxylon-type *Pinus* percentages increase and those of non-arboreal taxa decrease, suggesting the development of a subalpine parkland with no shrub understorey. Zone BL-1 contains between six and nine fire events per 1000 years. The time spanned by the events ranges from 24 to 108 years. Charcoal background levels are low (0.0 to 0.3 particles cm^{-2} $year^{-1}$).

Zone BL-2a (13 100–11 100 cal. BP) features increased pollen percentages of diploxylon-type *Pinus* (*P. contorta* and *P. jeffreyi*) and *Abies* (*A. magnifica* and *A. concolor*) and decreased percentages of herb taxa, suggesting that soils had become sufficiently developed to support forests. However, the understorey was probably not as dense as in modern montane forests of the Klamath region. *Isoetes* microspores first appear in this zone, suggesting the lake was more productive than before. The subzone contains many elements found in modern pollen spectra from upper montane-subalpine forests in the central Sierra Nevada and Klamath Mountains (Heusser, 1983; Anderson and Davis, 1988), but it lacks significant percentages of *Tsuga mertensiana* pollen. Macrofossils of *P. contorta, P. jeffreyi* and an unidentified five-needle pine were found in this zone.

The pollen assemblage suggests the continued development of subalpine forests as conditions became warmer and wetter than before. The frequency of fire events in this period ranges from five to eight per 1000 years. The duration of the fire events is 48 to 144 years, and charcoal background levels continue to be low (0.0 to 0.3 particles cm^{-2} $year^{-1}$).

Zone BL-2b (11 100–10 000 cal. BP) has been designated as a separate subzone based on changes in the pollen record as well as on sedimentologic, lithologic and charcoal data. *Cheilanthes*-type first appears and reaches high percentages in this zone. Most *Cheilanthes* ferns in the Klamath region grow on dry, rocky slopes, and elsewhere other species occur in chaparral or desert (Munz, 1973), indicating that conditions at Bluff Lake became warmer and drier than in the previous zone. However, the co-occurrence of rapid sedimentation (12 years cm^{-1} versus *c*. 48 years cm^{-1} for adjacent levels in the record), extremely high magnetic-susceptibility values, high charcoal-accumulation rates, and large numbers of corroded and unidentifiable pollen grains suggest that two or more sedimentological events occurred. This section of the core appears to have been deposited when slopes were unstable at the end of the Pleistocene, for it consists of clastic material, secondary charcoal and reworked pollen. Because it represents a sedimentological event and not a period of local fires and vegetational change, this section will not be discussed further.

Zone BL-3 (10 000–4450 cal. BP) is characterized by high percentages of *Quercus vaccinifolia*-type, *Q. garryana*-type and Cupressaceae. Slight decreases in undifferentiated and diploxylon-type *Pinus* (probably *P. jeffreyi*) occur. Haploxylon-type *Pinus* pollen percentages increase. Only trace amounts of *Abies* are present between *c*. 10 000 and 7400 cal. BP, suggesting that *Abies* is again locally absent and conditions are drier than before. *Abies* (probably *A. concolor*) and Poaceae pollen percentages start to increase after *c*. 7400 cal. BP, as *Quercus vaccinifolia*-type percentages decrease slightly. Some of the taxa (e.g., undifferentiated

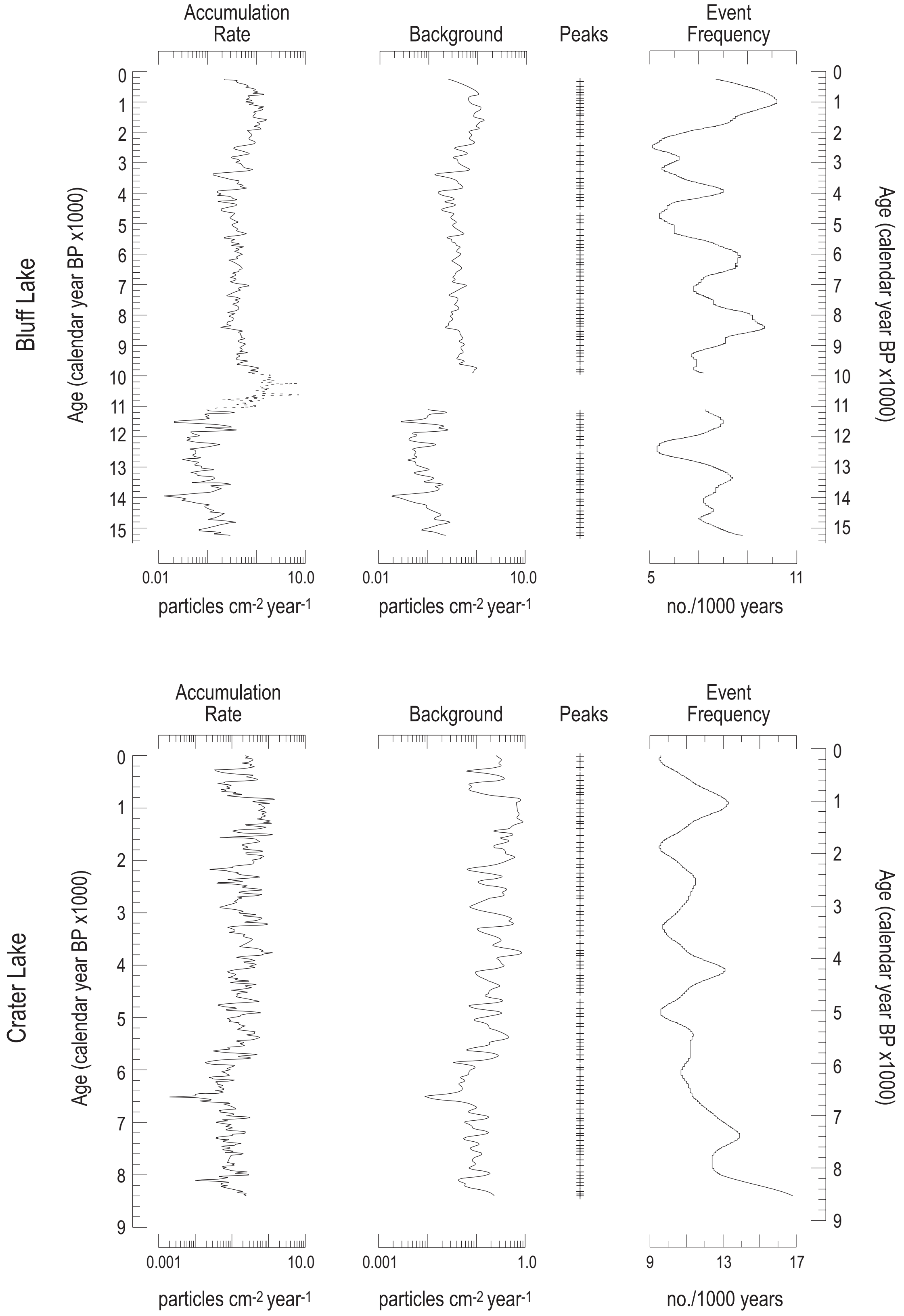

Figure 6 CHAR record for the last 15 300 years at Bluff Lake and CHAR record for the last 8400 years at Crater Lake. Accumulation rates were decomposed into background (also shown) and peaks (see text for discussion). Dashed line in the Bluff Lake graph represents a period of rapid sediment accumulation that was not included in the decomposition analysis. The event-frequency curves show the number of peaks per 1000 years.

Rosaceae and *Cercocarpus*-type) occur consistently throughout the zone in trace amounts (>1%), while others (e.g., *Ceanothus* and *Rhamnus*) increase slightly in this zone and reach their modern levels. *Isoetes* microspore percentages reach maximum levels at the top of this zone. Needles of *A. concolor, P. jeffreyi* and *Calocedrus decurrens* are present in this zone.

Haploxylon-type pine is most likely *Pinus lambertiana* or *P. monticola*. *Quercus garryana*-type pollen may be *Q. garryana* or *Q. kelloggii,* which would have occupied dry sites or have blown in from lower elevations. *Calocedrus decurrens* and *Juniperus occidentalis* probably contributed to the high Cupressaceae percentages. *Quercus vaccinifolia*-type and Rhamnaceae are major

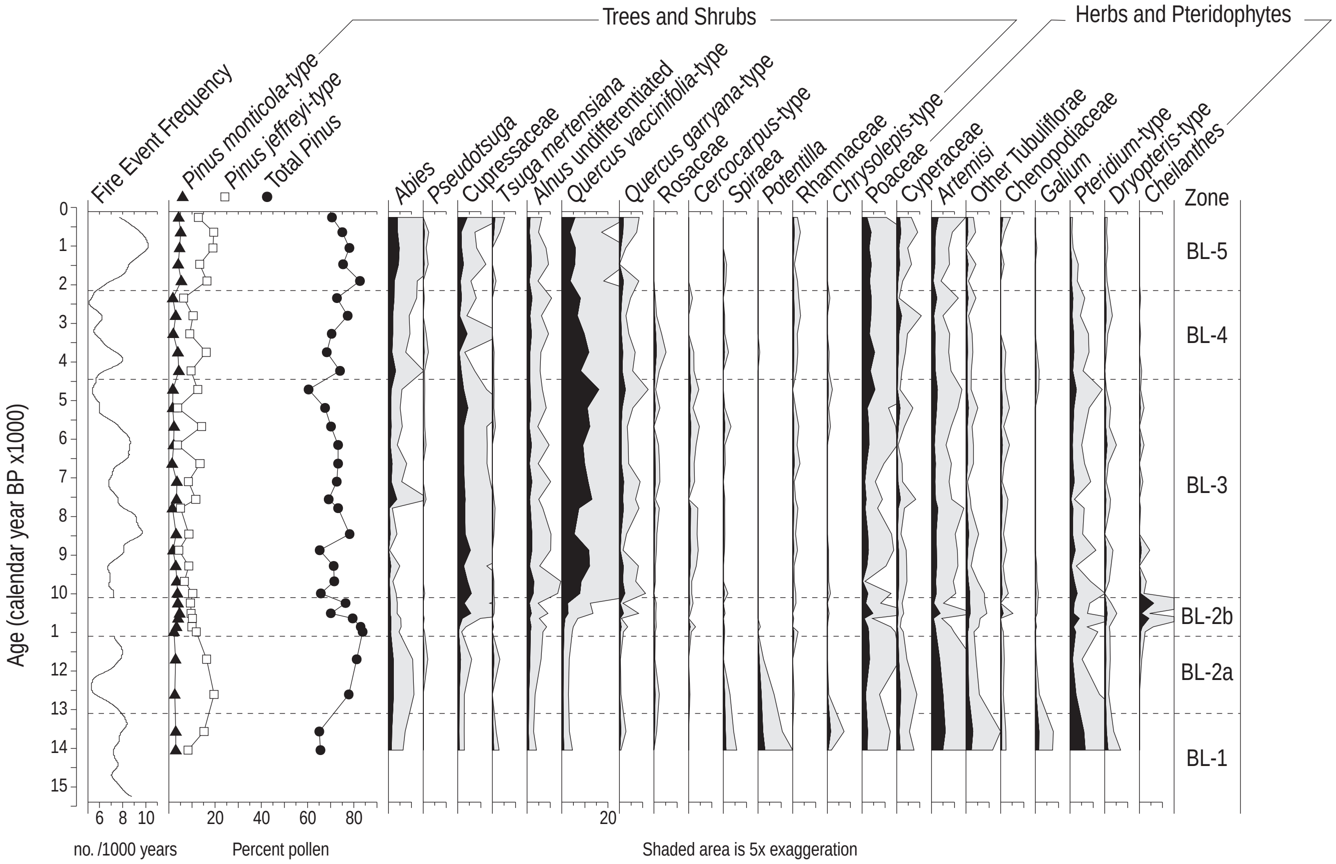

Figure 7 Fire-event frequency and pollen-percentage diagram of selected taxa for Bluff Lake. Shaded area represents exaggeration of 5×. Fire events span 24 to 180 years.

understorey components of Klamath montane forests, while *Cercocarpus* tends to grow in isolated patches on rocky, dry or cold sites, where it has a competitive advantage (Keeler-Wolf, 1987). This vegetation is similar to that found today north of Bluff Lake on dry slopes at lower elevations in the *Pinus ponderosa* vegetation zone (Vasek and Thorne, 1988). On the more xeric sites scattered *Pinus jeffreyi* would have intermingled with a continuous shrub layer on ultrabasic parent material. Mesic sites would have supported open stands of *Calocedrus decurrens, Pseudotsuga, Pinus monticola, P. jeffreyi, P. lambertiana* and *P. attenuata*. On non-serpentine soils *Q. garryana* and *Juniperus occidentalis* may have formed a woodland (Griffin, 1988). The charcoal-peak frequency fluctuates from six to ten fire events per 1000 years. The duration of time represented by an event ranges between *c.* 48 and 120 years. Charcoal background levels are higher than zone BL-2a, the values ranging from 0.2 to 1.0 particles cm^{-2} year^{-1}.

Zone BL-4 (4450–2150 cal. BP) contains high *Pinus* and Poaceae percentages. *Abies* pollen percentages increase during this time, indicating a change to more mesic conditions. *Quercus vaccinifolia*-type and Cupressaceae pollen percentages decline. The macrofossil data suggest that *Pinus* pollen came from *P. jeffreyi, P. monticola* or *P. albicaulis*. Needles of *A. lasiocarpa, A. concolor* and *A. magnifica* macrofossils were also recovered.

This assemblage suggests a change to a denser forest. Fire-event frequency is slightly lower during this period (five to eight fire events per 1000 years). The event durations in this zone span 48 to 180 years. The charcoal background levels are also slightly lower than the previous zone (0.1 to 0.9 particles cm^{-2} year^{-1}).

Zone BL-5 (2150 cal. BP to present) shows *Abies* at maximum percentages and increases in haploxylon-type and diploxylon-type *Pinus* and Cupressaceae percentages. *Quercus vaccinifolia*-type and *Pteridium*-type decrease to modern levels. Poaceae percentages remain high. *Pinus* macrofossils present in this zone include *P. monticola*, *P. jeffreyi* and *P. albicaulis*. Needles of *A. concolor, A. lasiocarpa, Pseudotsuga* and *Calocedrus decurrens* also occur.

This pollen assemblage resembles modern spectra from upper montane forests of the central Sierra Nevada (Anderson and Davis, 1988) and marks the establishment of the modern vegetation. The highest fire-event frequency (six to ten fire events per 1000 years) occurs in this zone. The duration of time for fire events is from 48 to 108 years. Charcoal background levels are at their highest (0.3 to 1.5 particles cm^{-2} year^{-1}) during this period.

Three fire events are recorded in the last 200 years, based on the analysis of the Bluff Lake short core (Figure 5). The fire events span 12 to 60 years and correlate well with independent evidence of fires based on tree-ring data. Fire events identified by charcoal peaks occurred at 1983–1995, 1911–1947 and 1827–1875. These peaks probably represent fires that occurred in 1990, 1938 (and/or 1908) and 1869 respectively. One watershed fire in 1899, identified in the dendrochronologic record, does not appear in the charcoal record. The background charcoal shows a steady decline in CHAR for the past 200 years from 1.6 to 0.6 particles cm^{-2} year^{-1}. The decrease in charcoal, most notable since the 1940s, may be the result of improved fire-suppression efforts.

Crater Lake

The pollen record from Crater Lake is divided into three local zones: CL-1 (*Pinus-Alnus-Quercus*), CL-2 (*Pinus-Abies*) and CL-3 (*Tsuga-Abies*). The charcoal analysis results are plotted in Figure 6 and selected taxa in Figure 8.

Zone CL-1 (8400–5650 cal. BP) contains high percentages of *Quercus vaccinifolia, Artemisia* and *Alnus* and low percentages of *Abies* and *Tsuga mertensiana*. Needles suggest the local presence of *T. mertensiana*. Haploxylon-type *Pinus* (probably *P. balfouriana, P. albicaulis* or *P. monticola*) and diploxylon-type (*P.

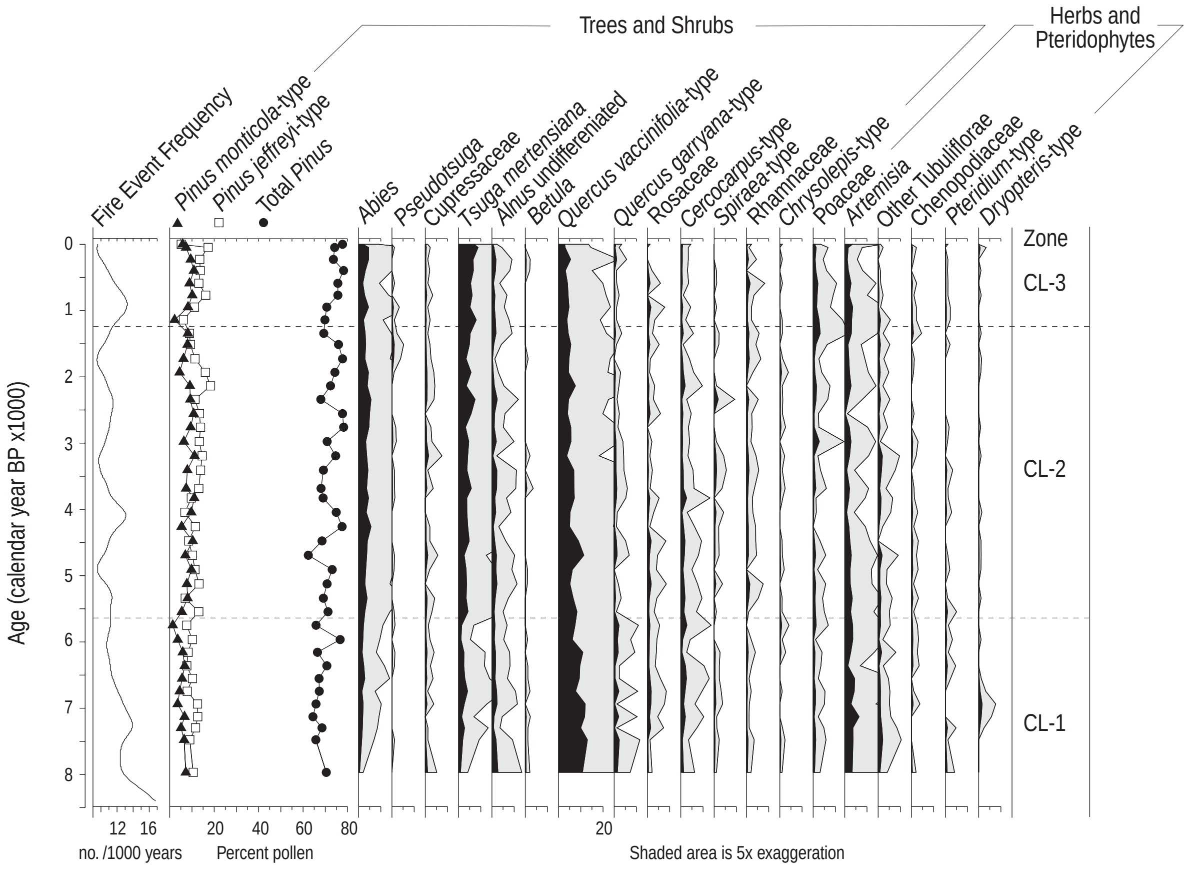

Figure 8 Fire-event frequency and pollen-percentage diagram of selected taxa for Crater Lake. Shaded area represents exaggeration of 5×. Fire events span 12 to 120 years.

contorta, or *P. jeffreyi*) percentages are slightly lower than after *c.* 5650 cal. BP.

Pinus was probably the forest dominant, with *Tsuga* and *Abies* less abundant than at present. *Q. vaccinifolia* probably grew at higher elevations than it does today. *Q. garryana* apparently also moved upslope but may not have grown at the site. The frequency of fire events ranges from 11 to 17 fire events per 1000 years. The duration of the events is from 13 to 72 years. Charcoal background levels are low (0.0 to 0.2 particles cm^{-2} year^{-1}).

Zone CL-2 (5650–1250 cal. BP) is characterized by a significant increase in *Abies*, which reaches modern levels. *Tsuga mertensiana* pollen percentages increase steadily in this zone, indicating a shift to a mixed montane forest. Decreasing percentages of *Quercus vaccinifolia* and *Artemisia* also suggest a vegetational shift toward a more closed forest. On the basis of macrofossils, *T. mertensiana*, *Pseudotsuga*, *A. magnifica* and *Pinus balfouriana* were present at the site. The charcoal-peak frequency during this period ranges from 10 to 13 fire events per 1000 years. The time spanned by the fire events ranges from 20 to 120 years. Background charcoal fluctuates between 0.1 and 0.9 particles cm^{-2} year^{-1}.

Zone CL-3 (1250 cal. BP to present) contains *Tsuga mertensiana* at maximum percentages, whereas *Abies* and *Pinus* percentages remain mostly unchanged from zone CL-2. *Quercus vaccinifolia* percentages continue to decrease, suggesting a retreat of oak downslope and/or increasingly closed canopy with the development of the modern mixed subalpine forest. Macrofossils of *A. magnifica* and *T. mertensiana* occur in this zone. The highest frequency (13 fire events per 1000 years) occurred between *c.* 800 and 900 cal. BP and then declined to present-day levels of 9 events per 1000 years. Event duration ranges from *c.* 19 to 60 years. Background charcoal levels were high (0.9 particles cm^{-2} year^{-1}) between *c.* 800 and 1250 cal. BP. Then levels fluctuated between 0.03 and 0.4 particles cm^{-2} year^{-1}.

Discussion

Comparison of fire history at Bluff Lake and Crater Lake

The vegetation and fire histories at Bluff Lake and Crater Lake trace the postglacial development of eastern Klamath Mountain forests and associated variations in the fire regime. The last 9000 years of the Bluff Lake fire-event record were plotted on the same scale as the Crater Lake record to compare the trends at the two sites. The millennial timescale records are quite similar (Figure 9). High fire-event frequency occurs at Bluff Lake and Crater Lake (10 fire events per 1000 years and 16 fire events per 1000 years, respectively) at *c.* 8400 cal. BP, whereas fire-event frequency was low (5 fire events per 1000 years at Bluff Lake and 9 fire events per 1000 years at Crater Lake) at *c.* 4800 cal. BP. The records exhibit moderate increases in fire frequencies at *c.* 4000 cal. BP (8 fire events per 1000 years for Bluff Lake and 13 fire events per 1000 years for Crater Lake) and at *c.* 1000 cal. BP (10 fire events per 1000 years at Bluff Lake and 13 fire events per 1000 years at Crater Lake). The similarity of the fire records probably reflects a common response to large-scale changes in climate, and we suggest that both sites were responding to warm, dry intervals in the early Holocene and during the ‘Mediaeval Warm Period’ (AD 900–1300; Bradley and Jones, 1992).

The fact that Bluff Lake lies in a southeast-facing basin of relatively dry aspect suggests that it should have been more likely to burn than Crater Lake, at a higher elevation and in a northwest-facing basin. The fire-scar tree-ring record also shows more fires at Bluff Lake in the last three centuries. We offer two explanations to account for the greater fire-event frequency evidenced at Crater Lake.

First, Bluff Lake has a slow sedimentation rate, so each 1 cm long sample represents a greater amount of time than at Crater Lake. Thus, the Bluff Lake record probably compresses several

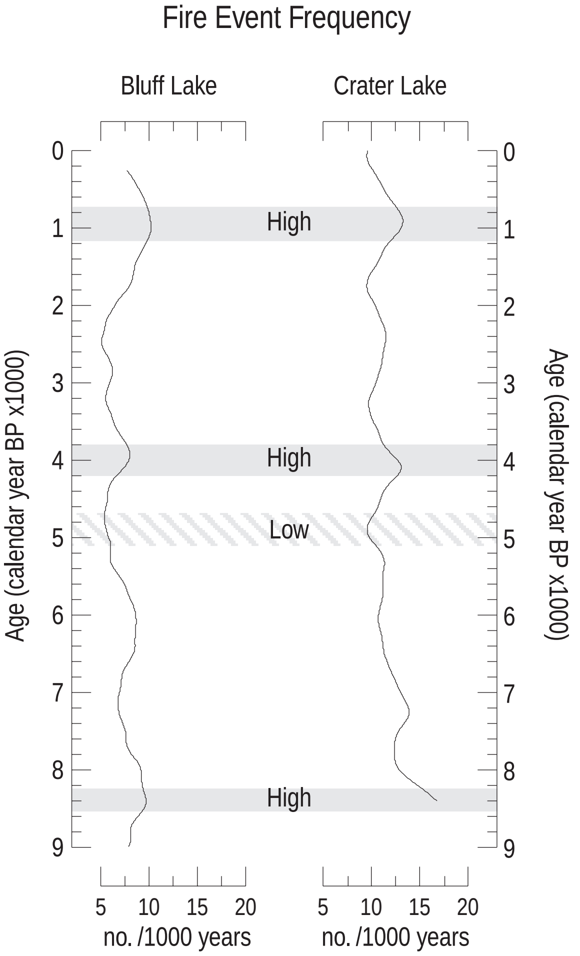

Figure 9 Fire-event frequency for Bluff Lake and Crater Lake showing trends for the last 9000 cal. BP.

fires into one sample, and by our technique would reduce the number of fire events per 1000 years. In contrast, the average deposition time at Crater Lake of 19 years cm^{-1} more closely matches the median fire-return interval (*c*. 11 to 14 years) based on tree-ring records. A charcoal peak in a sample at Crater Lake is more likely to represent fewer events than at Bluff Lake, and the number of fire events per 1000 years would be larger. Better resolution of the number of fire events will require examining sites with faster sedimentation rates.

Second, the higher fire-event frequency at Crater Lake may have been due to a greater number of anthropogenic fires in the lowlands adjacent to the site than at Bluff Lake, which is relatively distant from areas where humans might have set fires. Crater Lake lies just above the Scott River valley, a broad valley where fires may have been set regularly by prehistoric peoples. The Karok from northern California interior coastal mountains used ‘spot burning’ to increase or improve production of *Corylus cornuta, Xerophyllum tenax, Vaccinium* and grasses, as well as clearing areas to sow tobacco (Agee, 1993; Lewis, 1973). Fires started in the Scott River valley may have contributed charcoal to the Crater Lake basin, whereas anthropogenic fires may have been less common in the vicinity of Bluff Lake. Fire-history studies at low-elevation sites associated with prehistoric settlement are needed in order to determine if there is a correspondence between fire frequency and human occupation.

Comparison of regional records

Other records in western Oregon and northern and central California provide insights into the broad changes in vegetation and fire frequency that accompanied regional climatic changes. The regional comparison is provided by pollen data from Cedar Lake, eastern Klamath Mountains (West, 1989); Little Lake, central Coast Range, Oregon (Worona and Whitlock, 1995); Indian Prairie Fen, Cascade Range, Oregon (Sea and Whitlock, 1995); Point Reyes, central California Coast (Rypins *et al*., 1989); and Swamp Lake, Yosemite National Park, California (Smith and Anderson, 1992) (Figure 10). Charcoal data were available from Little Lake, central Coast Range, Oregon (Long *et al*., 1998), and Swamp Lake, Yosemite National Park, California (Smith and Anderson, 1992), for fire-history comparisons.

Lateglacial period (c. 16 800 and 11 100 cal. BP = c. 14 000 and 10 000 ^{14}C yr BP)

Bluff Lake supported a subalpine parkland with *Pinus* and *Abies* between *c*. 15 300 and 13 100 cal. BP. The climate was probably colder than present. After 13 100 cal. BP, increases in *Abies* and *Pinus* and decreases in herb taxa indicate development of a relatively closed forest. Haploxylon-type *Pinus* was most likely *P. monticola*, which at present can be found at elevations below that of *P. albicaulis* and *P. balfouriana* (Whipple and Cope, 1979). The latter two pines now occur at elevations above 2400 m and may have also grown at or near Bluff Lake prior to 13 100 cal. BP. Diploxylon-type *Pinus* was probably a mixture of *P. contorta* and minor amounts of *P. jeffreyi*. Modern subalpine forests on Mt Eddy support *P. jeffreyi* but not *P. contorta* (Whipple and Cope, 1979). On Scott Mountain-China Mountain crest area to the northwest of Bluff Lake a subalpine forest contains *P. jeffreyi*, *P. contorta* and *P. monticola*, and at higher elevations *P. balfouriana*, *Abies magnifica* and *Tsuga mertensiana* are present (Barker, 1984). The Lateglacial vegetation assemblages at Bluff Lake may have resembled these forests, with the notable absence of *T. mertensiana*. The increase in *Abies* after 13 100 cal. BP may indicate cooler conditions than at present but wetter than before. Generally low CHAR throughout the Lateglacial period suggests low amounts of available woody-fuel biomass and/or few fires as a result of the sparse understorey cover (Skinner and Chang, 1996) and conditions that were cooler and perhaps wetter than present.

At lower elevations in the Klamath Mountains, the vegetation at Cedar Lake was an open forest of *Pinus* and *Abies* and an understorey dominated by Ericaceae (West, 1989). From the relatively high amounts of *Pinus* pollen found in the Lateglacial, West (1989) inferred that temperatures were cooler than present. In the Sierra Nevada, subalpine and montane conifers were present by 14 500 cal. BP. The forest near Swamp Lake (Smith and Anderson, 1992) contained *Tsuga mertensiana*, *Pinus contorta*, *P. lambertiana*, *P. ponderosa*, *Abies magnifica*, *A. concolor*, *Calocedrus decurrens* and *Juniperus occidentalis*. Smith and Anderson (1992) estimated that temperatures were 3.7°C cooler in January and 3.0°C cooler in July than at present. The Lateglacial charcoal record from Swamp Lake also suggests few fires before 12 300 cal. BP.

Closed forests of *Pseudotsuga menziesii* and *Abies* with an understorey of Polypodiaceae were present on the central California coast at Point Reyes in Lateglacial time (Rypins *et al*., 1989). The climate was cool and also wetter than present between 14 500 and 11 300 cal. BP.

The Coast Range of Oregon was cooler and wetter than present from *c*. 14 250 to 12 400 cal. BP, and *Pseudotsuga menziesii*, *Abies*, *Tsuga heterophylla*, *Alnus rubra* and *A. sinuata* were present (Grigg and Whitlock, 1998). In the Oregon Cascade Range parkland vegetation was replaced by closed forests of *Abies lasiocarpa*, *A. amabilis*, *A. procera*, *A. grandis* and *Alnus* between 14 500 and 11 300 cal. BP during a time of cool, humid conditions (Sea and Whitlock, 1995).

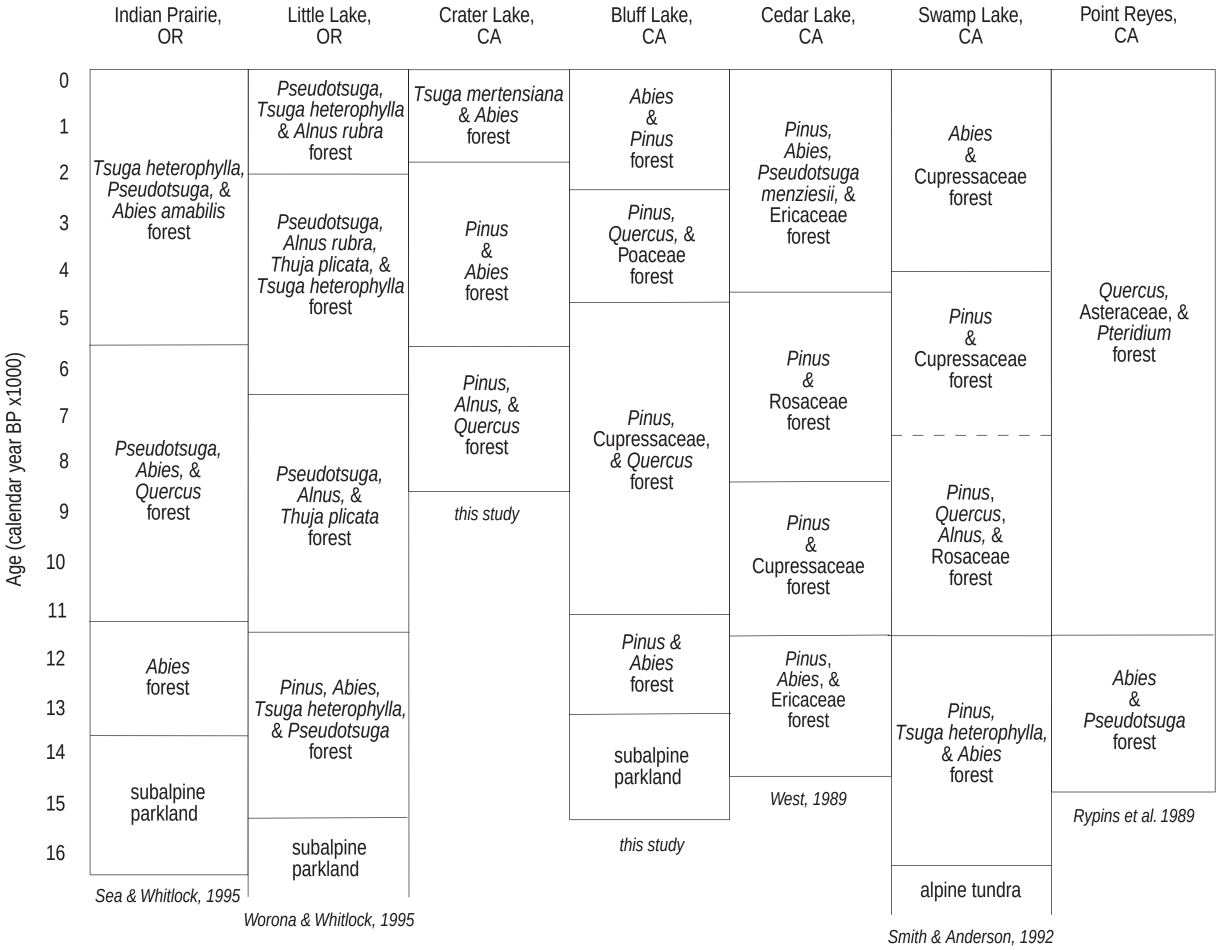

Figure 10 Summary of the postglacial vegetational history for selected sites in California and Oregon.

Early Holocene (c. 11 100 and 4450 cal. BP = c. 10 000 and 3950 ^{14}C yr BP)

Early-Holocene conditions were generally warmer and drier than the Lateglacial or late-Holocene intervals. These conditions are likely due to greater-than-present summer radiation values between 11 000 and 7000 cal. BP, which resulted in increased temperature, decreased effective precipitation and an expansion of the eastern Pacific subtropical-high pressure system off the Pacific coast (Thompson *et al.*, 1993).

At Bluff Lake *Pinus* was present though less abundant, and *Abies* declined significantly after *c.* 11 500 cal. BP, indicating that conditions locally were warmer and drier than at present or before this period. (*Abies* percentages increased briefly at *c.* 7400 cal. BP, which may signify a slightly wetter episode). Greater summer drought in the early Holocene apparently fostered the development of a shrub understorey with *Quercus vaccinifolia*, Rhamnaceae and Rosaceae. The Bluff Lake record suggests that *Quercus garryana* and Cupressaceae (most likely *Juniperus occidentalis*) moved upslope in response to drought. The vegetation is most similar to that found today at lower elevations in Scott Valley (Vasek and Thorne, 1988). The understorey taxa (*Quercus vaccinifolia*, Rhamnaceae and Rosaceae) are also found today in montane chaparral in areas of frequent stand-replacing fires or other disturbance (Skinner and Chang, 1996). Intensified or prolonged summer drought explains the increase in fire frequency at *c.* 6400 and *c.* 8400 cal. BP. High background charcoal levels suggest abundant woody-fuel biomass in the form of a chaparral-type understorey.

The forest at Crater Lake was composed primarily of *Pinus*, *Quercus vaccinifolia* and *Artemisia*, indicating that conditions were warmer and drier than present. After *c.* 5650 cal. BP *Abies* and *Tsuga mertensiana* increased in abundance, suggesting a cooling trend and/or increased precipitation. The charcoal record shows the highest fire frequency at *c.* 8400 cal. BP and a peak at *c.* 7200 cal. BP. As conditions became cooler and wetter, fire events decreased in frequency and charcoal background levels reached lowest values at *c.* 4800 cal. BP.

The forest at Cedar Lake was composed of TCT (most likely *Chamaecyparis lawsoniana*) with less *Pinus* than before (West, 1989). *Pseudotsuga menziesii* and *Abies* are notably absent in this part of the record, probably due to increased drought conditions. *Nuphar* and other emergent aquatic plants suggest a shallow lake. After 8600 cal. BP *Chamaecyparis lawsoniana* declined and *Pinus* became dominant again. Ericaceae and Rosaceae made up the understorey component, indicating a cooling trend; however, conditions remained warm and dry relative to present until *c.* 4100 cal. BP.

The record from Swamp Lake suggests the presence of lower Sierran montane taxa, with *Quercus* as a major component of the forest and *Abies* nearly absent until *c.* 7400 cal. BP (Smith and Anderson, 1992). Maximum charcoal concentrations were recorded during this warm, dry period. A cooler and/or moister trend occurred after 7400 cal. BP, when *Abies* increased and *Quercus* pollen decreased in abundance and charcoal concentrations decreased. Open *Quercus* woodland replaced *Pseudotsuga menziesii-Abies* forest at Point Reyes (Rypins *et al.*, 1989) from *c.* 11 300 to 8600 cal. BP. In addition, coastal scrub and grassland types increased in abundance, indicating warm, dry conditions.

In the central Oregon Coast Range drought-tolerant species including *Pseudotsuga*, *Quercus*, *Alnus rubra* and *Pteridium* expanded at the expense of Lateglacial mesophytes (Worona and Whitlock, 1995). Fires were more frequent at Little Lake from *c*. 7500 to 3700 cal. BP than at present (Long *et al*., 1998). The record from Indian Prairie Fen suggests that lower forest species moved upslope about 500 m in elevation in the early Holocene. This too is evidence that conditions were warmer than present (Sea and Whitlock, 1995).

Late Holocene (c. 4450 cal. BP to present = c. 3950 ^{14}C yr BP to present)

Slight increases in *Abies concolor, Pinus jeffreyi* and *P. monticola* suggest that conditions at Bluff Lake became cooler after *c*. 4450 cal. BP. Cupressaceae (probably *Juniperus occidentalis*) declined in abundance at this time. Decreases in *Quercus* beginning *c*. 3000 cal. BP suggest that a relatively closed forest canopy had developed. Modern forests of *Abies*, *P. jeffreyi* and *Calocedrus decurrens* were well established by *c*. 2000 cal. BP. Two peaks in fire-event frequency occurred in the late Holocene: the first at *c*. 4000 cal. BP was 8 events per 1000 years. The second peak (10 fire events per 1000 years) at *c*. 1000 cal. BP is the highest in the record. Modern forests of *Abies*, *Tsuga mertensiana* and *Pinus* were well developed at Crater Lake by *c*. 1200 cal. BP during a period of increased fire-event frequency.

At lower elevations, the Cedar Lake record places the establishment of modern forests of *Pseudotsuga, Abies, Pinus contorta* and Ericaceae at *c*. 4100 cal. BP, when conditions became cooler and wetter than before (West, 1989). At Swamp Lake *Calocedrus decurrens* and *Abies* replaced *Quercus* as important components of the forest *c*. 3900 cal. BP. Though conditions were cooler than before, moderate charcoal values indicate an increase in fire frequency and summer drought (Smith and Anderson, 1992). The Little Lake record indicates a closed mesophytic forest developed after 6300 cal. BP (Worona and Whitlock, 1995). By *c*. 2000 cal. BP the modern forest of *Pseudotsuga menziesii* was established as conditions became drier and fire frequency increased slightly (Long *et al*., 1998). In the Cascade Range modern forest of *Tsuga heterophylla, Pseudotsuga menziesii* and *Abies* was established near Indian Prairie Fen by 4500 cal. BP (Sea and Whitlock, 1995).

Conclusions

The postglacial vegetational and fire history from Bluff Lake and Crater Lake provides information on the responses of vegetation and fire regimes to millennial-scale changes in climate. Although the changes in vegetation and fire regimes are subtle in the Klamath region, they are similar to those inferred from palaeoecological records in other regions. Several conclusions can be drawn from this study.

(1) The fire history of the last 8400 years is similar at Bluff and Crater Lakes, implying that fire occurrence increased in both regions during dry periods. For example, fires were frequent at both sites *c*. 8300 and 4000 cal. BP and during the ‘Mediaeval Warm Period’. The number of fire events per millennium seems to be greater at Crater Lake, even though this site is located in a northwest exposure, where one would presume that cooler, wetter conditions would mitigate the occurrence of fires. However, it is important to note that each fire event (or charcoal peak) represents relatively long periods and probably multiple fire events. Crater Lake features a higher fire-event frequency than at Bluff Lake, but each event may reflect fewer but more severe fires. To address this issue will require sites with faster sedimentation rates to allow detection of single fire events.

(2) Lateglacial conditions were cooler than present and supported a subalpine parkland at Bluff Lake after deglaciation of the site. As the climate warmed and became more mesic, both high and mid-elevation conifers such as *Abies magnifica*, *Pinus albicaulis*, *P. jeffreyi* and *P. monticola* may have colonized the site. The resulting assemblage has no modern analogue, suggesting that winters were cooler and wetter and summers were warmer than present. Fires were infrequent and charcoal production was low. Increased summer insolation caused warmer, drier conditions in the early Holocene. The reduction of *Abies* and subalpine taxa from Bluff Lake was probably a result of the more xeric conditions. Open forests of lower-elevation woodland taxa (*Quercus garryana* and *Juniperus occidentalis*) and mid-elevation conifers were established, along with a montane chaparral-type shrub understorey dominated by *Quercus vaccinifolia*. Increased fire-event frequency and charcoal production suggest that fire became an important element in maintaining the xerophytic vegetational assemblage. A cooling trend after *c*. 7400 cal. BP is noted in the California records (Cedar Lake, Swamp Lake and Bluff Lake); however, conditions remained warmer and drier than present (as seen in the Crater Lake record). The late Holocene is marked by increasingly cooler conditions than the early Holocene as a result of decreased summer radiation and wetter conditions due to a weakened subtropical high. *Abies* and *Pinus* became more abundant in the late Holocene at Bluff Lake owing to moister conditions. There is a notable decrease in *Quercus vaccinifolia* and Cupressaceae *c*. 4000 cal. BP, which may be due to establishment of a more closed forest at the site. After *c*. 2000 cal. BP forests of modern composition were established at both lakes. Fire-event frequencies reach high levels *c*. 1000 cal. BP at both lakes before returning to present-day levels of between 7 and 9 fire events per 1000 years.

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