The Holocene 16,4 (2006) pp. 505–517

A postglacial palaeoecological record from the San Juan Mountains of Colorado USA: fire, climate and vegetation history

Jaime L. Toney[1]* and R. Scott Anderson[1,2,3]

([1]Laboratory of Paleoecology, Bilby Research Center, Box 6013, Northern Arizona University, Flagstaff AZ 86011, USA; [2]Quaternary Sciences Program, Box 5644, Northern Arizona University, Flagstaff AZ 86011, USA; [3]Center for Environmental Sciences & Education, Box 5694, Northern Arizona University, Flagstaff AZ 86011, USA)

Received 17 February 2005; revised manuscript accepted 1 December 2005

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Abstract: Continuous sediment, charcoal and pollen records were developed from a ~4.5 m sediment core from Little Molas Lake (LML), 3370 m elevation, San Juan County, CO. LML formed by 11 200 cal. BP subsequent to glacial retreat. Turbated clay and gyttja was derived from in-lake productivity and outwash sediments from the drainage basin from ~11 200 cal. BP until ~10 200 cal. BP. Cessation of glacial input and replacement of tundra with *Picea* forest correlates with the termination of the Younger Dryas and indicates warming. An increase in diploxylon pollen (cf. *P. ponderosa*), probably from lower elevations, reflects the influence of the southwestern monsoon *c.* 10 160 cal. BP. Pollen ratios indicate that *Picea* and other conifers persisted near the lake for the remainer of the Holocene. The driest Holocene period occurs *c.* 6200 to 5900 cal. BP, when lake levels were the lowest as indicated by all the proxy records. Wetter conditions during the last *c.* 2600 cal. BP favoured the expansion of *P. edulis* and *P. ponderosa*. Lateglacial fire events occurred on average every 65 years with a doubling of the fire return interval in the early Holocene. The former may reflect an increase in biomass for burning during a period of rapid vegetation turnover. The lowest fire event frequency occurs during the Neoglacial (after *c.* 4100), during a period of moister and cooler climate. The most recent pronounced peak in charcoal coincides with the historically documented AD 1879 Lime Creek Burn.

Key words: Palaeoecology, vegetation history, Southern Rocky Mountains, pollen analysis, charcoal analysis, Holocene, fire history.

Introduction

The last decade has witnessed a renewed interest in the relationship between vegetation change and disturbance in forests of western North America through a combination of pollen and high-resolution charcoal analysis. For instance, Millspaugh and Whitlock (2002) used high-resolution sedimentary charcoal to reconstruct centennial-scale fire history in Yellowstone. Similar studies have come from the Pacific Northwest (Long *et al.*, 1998), western Canada (Hallett and Walker, 2000; Hallett *et al.*, 2003) and the California mountains (Anderson and Smith, 1997; Mensing *et al.*, 1999; Mohr *et al.*, 2000; Brunelle and Anderson, 2003). Each study focused on a different vegetation type, but most of these studies were from low to middle elevation forests.

Little research has focused on the long-term vegetation trends and fire history of the subalpine forests of the southern Rockies, composed primarily of *Picea engelmannii* (Englemann spruce) and *Abies lasiocarpa* (subalpine fir). The *Picea–Abies* forest association presently covers large areas of the subalpine there (Komarek, 1994), but its extent and the importance of fire on millennial timescales is largely unknown. Several recent studies, including this one, focus on better understanding the relationship between forest types and fire extent (Brunelle and Whitlock, 2003; Wright and Agee, 2004; Whitlock *et al.*, 2004) We present data from a small subalpine lake, Little Molas Lake (LML), in the San Juan Mountains of southwestern Colorado, reflecting the history of fire and vegetation at high elevations. The study of Little Molas Lake is part of a regional study of vegetation change and fire frequency in the montane to subalpine forests in the Southwest using pollen and charcoal from lake sediments (Anderson *et al.*, 2004).

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*Author for correspondence (e-mail: jaime.toney@nau.edu)

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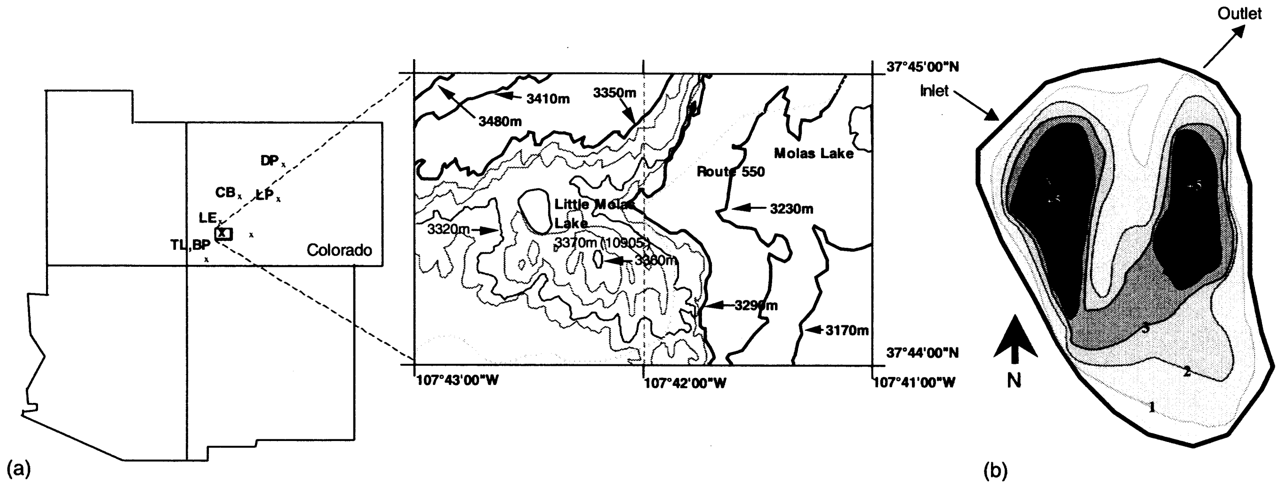


Figure 1 (a) Southwestern United States site location map. Other lake sites within the San Juan Mountains and elsewhere in Colorado are depicted by initials: Devlins Park (DP), Twin Lakes (TL), Beef Pasture (BP), Crested Butte (CB), Lake Emma (LE), Lost Park (LP) and Molas Lake (ML). Little Molas Lake is depicted by 'x' inside the boxed region in Southwestern Colorado. (b) Bathymetry map of LML, c.i. = 1 m, coring location is depicted by 'x'

The record from LML is important for several reasons. First, several authors have suggested a relationship between fire history and the development of the Southwest monsoon (eg, Swetnam and Betancourt, 1990; Swetnam *et al.*, 1999; Kitzberger *et al.*, 2001). Because of its location near the monsoon's northern limit, the record from LML documents periods when the monsoon was strong in the Southwest, and aids in recognizing conditions preceding fires and large-scale changes in climate.

Second, the LML record provides a minimum confining age for the timing of deglaciation in the San Juan Mountains, which, except for relatively few scattered lake studies, has been based upon relative correlations of undated glacial moraines in the region (Atwood and Mather, 1932). Other lake sediment studies constrain deglaciation to an age range of < ~15400 ^{14}C yr BP (Maher, 1972) to before ~9000 ^{14}C yr BP (Andrews *et al.*, 1975). Site-specific controls on deglaciation have not been analysed, although aspect appears to be important, with north-facing cirques remaining glaciated longer than south-facing cirques (Elias *et al.*, 1991). Basal radiocarbon dates from LML are important in determining potential age discrepancies and providing additional evidence on whether controls on deglaciation were site specific.

We used fine-interval sediment sampling to produce our detailed record of vegetation, fire and climate, concentrating on the following questions: (1) how has high-elevation subalpine forest composition changed in response to postglacial climate change; (2) what is the temporal pattern of fire frequency and intensity during the late- and postglacial periods; (3) how does the overall LML record relate to other regional reconstructions of fire and vegetation?

Location of site

Little Molas Lake is located in San Juan County, Colorado in a south-facing cirque at 3370 m elevation (37°44′30″N, 107°42′30″W, T40N, R8W, Sec 11) (Figure 1a). Maximum depth of the lake when visited in October 2000 was 5.6 m (Figure 1b). The lake basin is formed by a glacially eroded bedrock, composed primarily of Tertiary-age quartzites that overlie Carboniferous sediments (Blair *et al.*, 1996).

The climate of southwest Colorado is typified by a biseasonal precipitation regime (http://www.wrcc.dri.edu/summary/climsmco.html, last accessed 17 March 2006). Average precipitation at Silverton, Colorado (2865 m elevation, *c.* 10 km NE of LML) is 62 cm/yr, with 30% falling predominantly as snow from December through March, and 35% falling as rain from July through September. Average temperature ranges for winter and summer are −18.8 to −17.2 to 1.1 to 2.6°C and −0.1 to 3.3 to 20.0 to 22.8°C, respectively.

Alpine vegetation in the San Juan Mountains is dominated by deep-rooted mat plants, Poaceae (grass) and Cyperaceae (sedge), and occupies high-elevation sites above 3300 m. Below this is (1) subalpine: *Picea engelmannii, Abies lasiocarpa* and *Pinus contorta* (lodgepole pine), 2700–3300 m; (2) montane/mixed conifer: *Pseudotsuga* (Douglas-fir), *Abies, Populus* (quaking aspen), and *Pinus contorta* and *P. ponderosa,* 2500–2700 m; (3) foothills: *Quercus* (oak), *Cercocarpus* (mountain mohagany) and Poaceae, with occasional *Pinus edulis* (Colorado piñon) and *Juniperus* (juniper), 1800–2500 m (Weber, 1976; Binkly, 2003).

LML is located within an open *Picea* woodland and subalpine meadow in the subalpine zone. The area around the lake was burned in the Lime Creek fire of 1879, an intense fire that started SW of the lake, burning *c.* 10500 ha (Thompson, 2002; Maher, 2003). The fire left pockets of unburned forest in the drainage basin. Dominant trees in the watershed include *Picea englemannii* and *Pinus contorta* var. *latifolia. Salix* sp. (willow), Cyperaceae and *Juncus* sp. (rush) are common along the lake border (plant identification after Weber and Wittman, 2001). Other plants found within the vicinity include *Potentilla* sp. (cinquefoil), *Taraxacum officinale* (dandelion), *Achillea millefolium* (yarrow), *Hymenoxys hoopesii* (orange mountain daisy), *Fragaria virginiana* (strawberry), *Bromus inermis* (smooth brome), *Poa* cf. *pratensis* (bluegrass), Brassicaceae (mustard family), *Epilobium angustifolium* (fireweed), *Geum macrophyllum* (big-leaved avens), *Trifolium* sp. (clover), *Geranium richardsonii* (geranium), *Arenaria* sp. (sandwort), *Phleum commutatum* (alpine timothy), *Penstemon* sp. (snap-dragon), *Heterotheca pumila* (chrysopsis), *Antennaria* sp. (pussytoes), *Cirsium* sp. (thistle) and *Polygonum arenastrum* (knotweed). *Potamogeton* sp. (pondweed) and *Myriophyllum verticillatum* (whorled-leaved water milfoil) are common within the lake. At least nine species of *Artemisia* (sagebrush or

Table 1 Age data for Little Molas Lake, San Juan Mountains, CO

Depth (cm)	Core	Dating method	Sample description	^{14}C yr BP	Lab #	Intercept age	+error	−error	yr AD
0	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−45	x	x	2000
1	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−39	x	x	1994
2	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−34	x	x	1989
3	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−29	x	x	1984
4	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−23	x	x	1978
5	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−18	x	x	1973
6.5	2	^{137}Cs	5 cc bulk sediment	x	USC Geology	−8	x	x	1963
7	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−8	x	x	1963
8	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	−2	x	x	1957
9	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	2	x	x	1953
10	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	8	x	x	1947
11	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	13	x	x	1942
12	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	19	x	x	1936
13	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	24	x	x	1931
14	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	29	x	x	1926
15	2	^{210}Pb	5 cc bulk sediment	x	USC Geology	34	x	x	1921
32–33	3	^{14}C	bulk sediment, <250 μm	1300±40	Beta-192392	1260	20	100	x
34–36	3	^{14}C	spruce needles	4620±40	Beta-177158	5370	25	25	x
87–89	3	^{14}C	spruce needle and seed	2630±40	Beta-175194	2760	25	25	x
164–165	3	^{14}C	spruce bark fragments	5170±44	AA-45143	5920	60	10	x
290–291	3	^{14}C	spruce bark and seed	8940±54	AA-45142	10 150	40	230	x
406–409	3	^{14}C	bulk, organic sediment	16 840±80	Beta-157386	20 100	500	500	x
409–412	3	^{14}C	aquatic insects	9830±360	AA-49378	11 200	730	510	x

Note: cal. BP is in reference to years before AD 1955.

wormwood) exist within the San Juan Mountains (Komarek, 1994; Weber and Wittman, 2001) and could be potential sources of pollen input to the lake in the present and in the past.

During the Pinedale glaciation (Late Wisconsin, 23 000–12 000 cal. BP) (Armour *et al.*, 2002), 5000 km^2 of ice covered the San Juan Mountains in the form of valley glaciers (Atwood and Mather, 1932), regional ice fields and transection glaciers (Cararra *et al.*, 1984). LML, located at 3370 m elevation, was at or just below the equilibrium line altitude (ELA) during the Pinedale glaciation (Leonard, 1984). It is presently at the head of the Animas River drainage, which was covered by a large valley glacier that extended 75 km and covered 600 km^2 (Atwood and Mather, 1932).

Methods

Core collection

Two 5-cm diameter, 4.5-m long cores (LML Cores 1 and 3) were recovered from the deepest section of the lake (Figure 1b) using a Livingstone piston corer from a stabilized pontoon boat in October 2000. A short core (LML Core 2) was obtained using a plexiglass tube less than 1 m from Core 3 to retrieve the unconsolidated upper sediments at the sediment–water interface. The resulting analyses were taken from Cores 2 and 3.

Age determination

The LML chronology was developed from AMS radiocarbon, ^{137}Cs and ^{210}Pb analyses. Material for AMS dates consisted of terrestrial plant remains and aquatic invertebrate remains (Table 1). Samples for AMS dating were initially dried and weighed before submission. Radiocarbon ages were calibrated to calendar ages using CALIB version 4.3 (Stuiver *et al.*, 1998).

Samples for ^{210}Pb and ^{137}Cs dating consisted of whole (3–5 g) sediment dried to constant weight in an oven. Excess ^{210}Pb and fallout ^{137}Cs activities were measured non-destructively by gamma spectrometry using a high-resolution, low-background well-type Ge detector (R. Ku, personal communication, 2004).

Lithology and magnetic susceptibility

Whole-core magnetic susceptibility (MS) was measured for each continuous centimetre with a Sapphire Instruments SI2B meter. MS is used to identify allochthonous, minerogenic material in the sediment core that originates from erosion of the watershed or deposition from a volcanic tephra (Dearing, 1999). Lithology and wet Munsell colour was described from split core segments. Total carbon (TC) was analysed at 5-cm intervals by 1000°C combustion and measurement of the resultant CO_2 with a coulometer. Total inorganic carbon (TIC) was measured every 10-cm by acidifying samples in 2N $HClO_4$ and coulometric measurement of CO_2 produced. Total organic carbon (TOC) was calculated by subtracting TIC from TC.

Charcoal and macrofossils

Samples 5 cm^3 were taken for each centimetre of depth. Each sample was deflocculated in a solution of 10% $Na(PO_3)_3$ (sodium hexametaphosphate) for two to five days, then wet-sieved (250 μm and 125 μm screens). Charcoal particles >100 μm reflect occurrence of local fires, because particles of this size do not travel far from their source (Whitlock and Anderson, 2003). Charcoal particles were counted and tallied using a dissecting microscope at ∼50× magnification. Macrofossils were identified from the same samples as the charcoal.

High-resolution sedimentary charcoal analysis followed methodologies of Long *et al.* (1998) and Whitlock and Anderson (2003). Charcoal accumulation rates (CHAR) were decomposed into background and peaks components using the Charcoal Analysis Programs (CHAPS). The background component considers variations in overall charcoal production and sedimentation while the peaks component registers fire events. A fire event is determined when the CHAR of a sample exceeds background level by a specified peak threshold ratio of 1.0 or greater (Whitlock and Anderson, 2003). Using a

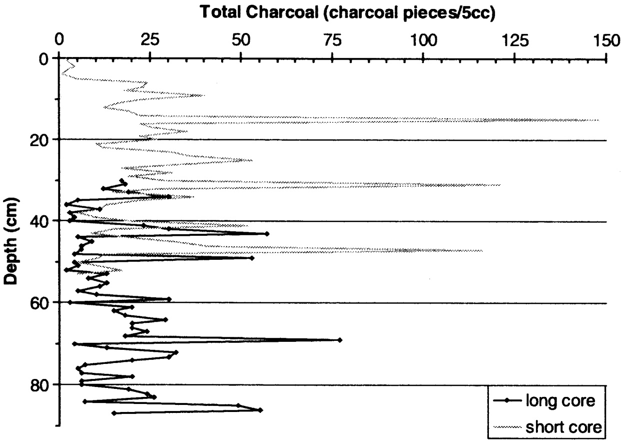


Figure 2 Correlation between the charcoal records of Little Molas Lake Cores 2 and 3

sensitivity analysis of different values of the locally weighted mean window width, peak-to-mean ratio threshold and window width for estimating peak magnitude and frequency, showed values of 300 years, 1.0; and 200-yr smoothing over a 1000-yr interval produced interpretable results. Other values were rejected, for example because a peak-to-mean ratio threshold of 1.2 removed virtually all the charcoal peaks from the record, including known historical events, and window widths for estimating peak frequency of less than 300 years caused greater between-sample variability than was realistic. Using a window width of 500 years removed most of the variability from the curve.

Pollen

Subsamples of 1 cc each were collected at 10-cm intervals. Pollen extraction methods were modified from Fægri *et al.* (1989). Two *Lycopodium* tracer tablets were added to each sample for pollen concentration calculation. Sample residues were stained with safranin-O and mounted in silicone oil (2000 cs).

Counting was performed at 400 × magnification on a compound light microscope. At least 300 terrestrial grains per slide were identified. The pollen reference collection at the Laboratory of Paleoecology (LOP) and published keys (eg, McAndrews *et al.*, 1973; Kapp *et al.*, 2000) were used as the basis of identification. Pollen percentages were calculated and plotted using TILIA (Grimm, 1993). *Pinus* pollen was divided into four categories: diploxylon (locally, *P. contorta* or *P. ponderosa*), large haploxylon (bristlecone, *P. aristata*; limber, *P. flexilis*; or Mexican white, *P. strobiformis*), small haploxylon (*P. edulis*) and undifferentiated (Jacobs, 1985). *Pinus* pollen grains were classified as haploxylon if verrucae were present on the leptoma and as diploxylon if verrucae were not present. Haploxylon grains with a grain length of less than 65 μm were considered 'small', while those greater than 65 μm were considered 'large'.

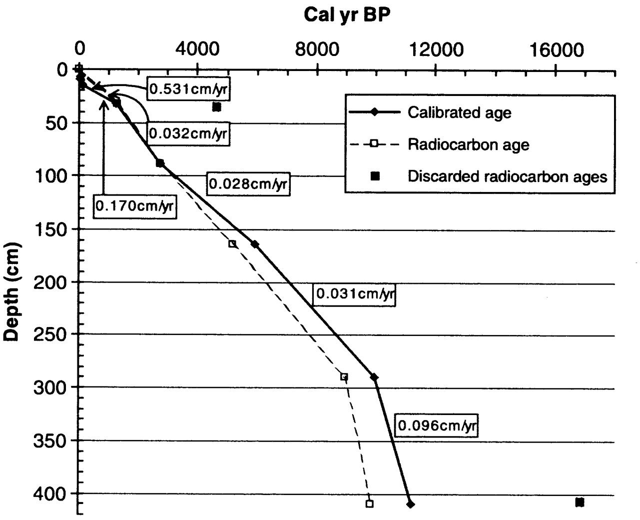


Figure 3 Little Molas Lake age model using linear interpolation

We used the CONISS-cluster analysis program in TILIA (Grimm, 1993) to determine pollen zone boundaries. Zones were defined based on the stratigraphically constrained incremental sum of squares. Pollen zone boundary ages were estimated by linear interpolation between calibrated radiocarbon-dated intervals.

Results

Age determination

Seven AMS dates and one ^{210}Pb/^{137}Cs date series constrain the timing of events and allow for sediment accumulation rate calculations (Table 1). A seemingly old basal date on bulk sediment returned an age of 20 090 cal. BP at 407.5 cm. A second basal date from 410 cm on Cladocera returned an age of 11 200 cal. BP. Four additional dates occur in stratigraphic order, but a sample at 34–36 cm on *Picea* needles returning a reversed age of 5370 cal. BP (Beta-177158) was considered too old and was not used in age-model construction. Although chronologies can be used to match the top of the long core with the bottom of the short core, charcoal peaks from cores 2 and 3 matched well by depth (Figure 2); therefore, Core 2 was used from 0 to 30 cm, and Core 3 was used for the rest of the record.

Sedimentation rates are based on linear interpolation between calibrated radiocarbon dates and the ^{210}Pb series. The sedimentation rate is high (0.096 cm/yr) during the lateglacial and postglacial from 11 400 to 9950 cal. BP (Figure 3). The rate declines to 0.031 until 5920 cal. BP, further declines to 0.028 cm/yr through 2760 cal. BP and rises from 0.032 cm/yr to 0.170 cm/yr from 1260 cal. BP to 120 cal. BP, and then to 0.531 cm/yr through present. This rapid sedimentation rate is consistent with the flocculent, non-compacted nature of sediments at the top of lake sediment cores.

Magnetic susceptibility

Whole-core MS is high at the base of the core 450 cm (Figure 4). Two large peaks in MS occur at 447 and 422 cm (11 580 and 11 330 cal. BP). The latter peak gradually tapers off by 396 cm (11 050 cal. BP) to the background level of ~0.30 cgsu (× 10 000) and remains low for the rest of the record.

Carbon

Inorganic carbon (IC) never exceeds 1% by weight. Organic carbon (TOC) values remain low in the lateglacial and early Holocene from 406 to 227 cm (11 380 cal. BP to 10 240 cal. BP) (Figure 4). Values remain at ~14% until 159 cm (5720 cal. BP), after which they rise to ~16% until 70 cm (2300 cal. BP). Major troughs in the organic carbon record correspond with peaks in MS and to low numbers of Cladocera.

Charcoal

Peaks in charcoal occur frequently throughout the LML record (Figure 5). Average peak frequency for the entire record is 7.8 events per 1000 years with a minimum of 4.9 and a maximum of 15.6 events/1000 years (Figure 5). Fire event frequency reached a maximum in the early Holocene, but began to decline by 10 500 cal. BP. Prior to 10 500 cal. BP, peak frequency is 15.3 events per 1000 years. Frequency declined to

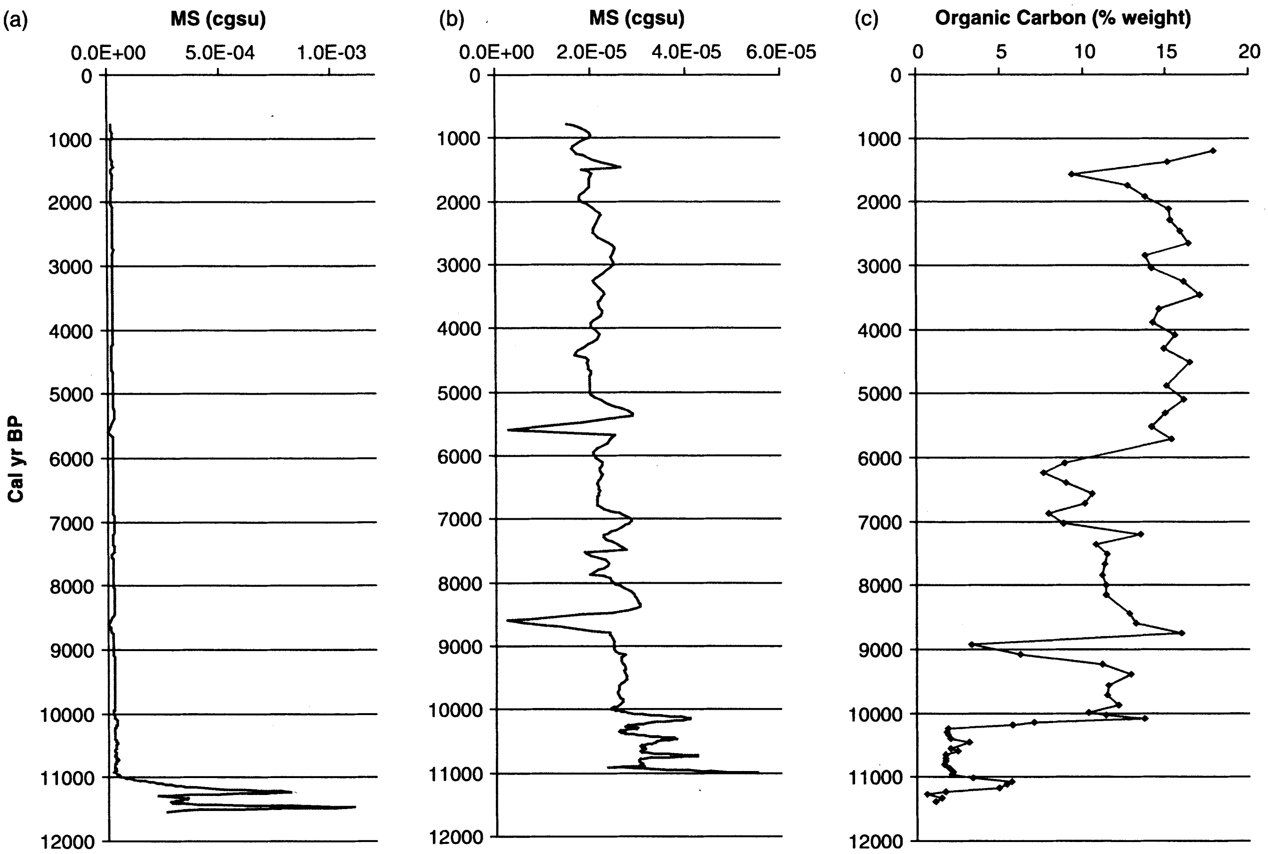


Figure 4 Little Molas Lake data plotted versus cal. yr BP. (a) MS data, entire record from Core 2. (b) Magnified MS record between 30 and 400 cm from Core 2. (c) Organic carbon data, entire record from Core 2

c. 6.5 events/1000 years between 8900 and 7150 cal. BP, rose to *c.* 8 events/1000 years from 6640 to 5200 cal. BP, and declined to below 5 events/1000 years by *c.* 3500 cal. BP. The highest Holocene frequencies are centered around *c.* 2200 cal. BP.

Macrofossils

Few terrestrial macrofossils are found from the base of the core to *c.* 280 cm (Figure 6). Above 280 cm (9620 cal. BP), *Picea* needle fragments and seed wing fragments occur sporadically throughout the rest of the core. Conifer macrofossils increase substantially above 98 cm (3170 cal. BP).

Pollen

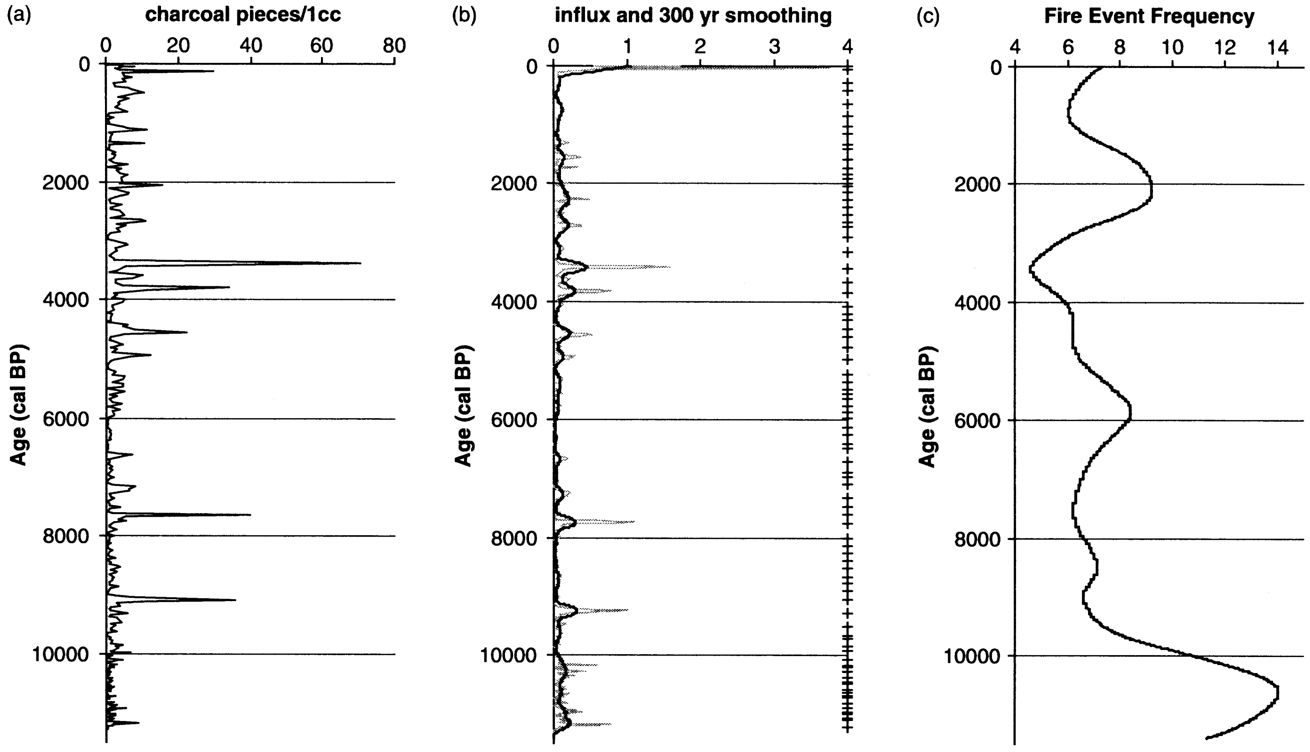
Four pollen zones were recognized: LML-1 (11 400–10 520 cal. BP); LML-2 (10 520–9000 cal. BP); LML-3 (9000–2650 cal. BP); and LML-4 (2650 to present or AD 2000) (Figure 6). LML-4 was further divided into two subzones. In addition, we calculated three other statistics: the Spruce/Total Pine (S/P) ratio tracks the density of *Picea* forest; the Spruce/*Artemisia* (S/A) ratio controls for changes in depositional sources; and the Spruce+Fir+Pine/Non-arboreal (C/NAP) is used as a measure of conifer density versus non-arboreal types, including herb and shrub taxa (Maher, 1961, 1972; Petersen and Mehringer, 1976; Petersen, 1981, 1982, 1985, 1988).

LML-1 (11 400–10 250 cal. BP) pollen spectra are characterized by low pollen concentrations and high spruce percentages (Figure 6). In LML-1 and 2, *Pinus* undifferentiated and *Artemisia* percentages are highest while *Picea* percentages are variable. Other prominent taxa include Rosaceae, *Ambrosia*, Poaceae and *Dryas*. Aquatic/wetland types include *Salix*, *Typha* and *Botryococcus*. At 10 250 cal. BP conifers become more abundant, marking the end of the LML-1.

The S/P ratios peak above the mean (0.6) between 11 100 and 10 520 cal. BP (Figure 7). Maher (1972) interpreted high S/P ratios to indicate higher forest density or absence of forest disturbance. However, Carrara *et al.* (1984) interpreted increasing S/P ratios as indicating a rising treeline. We use the S/P ratio to indicate a combination of forest density and higher treeline, which is supported by macrofossil evidence.

Total pollen concentrations and tree pollen percentages increase in LML-3, remaining fairly constant from 9000 to 2650 cal. BP (Figure 6). *Picea*, small haploxylon *Pinus*, *Pinus* undifferentiated and *Artemisia* decline and pollen percentages remain depressed until after 3600 cal. BP. Total *Pinus* and Cheno-ams percentages are relatively high throughout LML-3. S/P and C/NAP ratios are above the mean throughout much of LML-3. These peaks correlate with the S/A ratio peaks until 6200 cal. BP, after which the two ratios fall out-of-phase. Throughout the rest of the record the S/A ratio and the C/NAP ratio fall well below the mean; whereas, the S/P ratio remains high until after 1620 cal. BP (Figure 7).

LML-4 (2650 cal. BP to present) is characterized by an initial decline in diploxylon *Pinus* pollen and the increase in small- and large-haploxylon *Pinus*, *Artemisia*, Poaceae and aquatic percentages. Diploxylon *Pinus* percentages rebound after 400 cal. BP, an increase from ~0% to ~25%, along with a decrease in shrub and herb taxa. Other trends include a decline in pollen concentration, and Cheno-ams and *Artemisia* percentages after 400 cal. BP. The S/P ratio declines with the exception of a peak from 2080 to 1610 cal. BP. The S/A peaks also decline until 1780 cal. BP. After *c.* 1780 cal. BP the S/A and S/P ratios decline to near zero. Based on the plotted ratios, C/NAP peaks above the mean (1.6) just after AD 1950.



Note: Peak Start is represented by a '+' symbol. Peak-to-mean ratio = 1.0.

Figure 5 Little Molas Lake, San Juan Mountains, CO (3370 m). (a) Raw charcoal counts plotted versus age. (b) Charcoal influx and the peak-start. (c) Inferred fire event frequency (1000 window:200 yr smoothing)

Discussion

Timing of deglaciation at LML

Poorly sorted, inorganic sediment with high MS at the base of the core suggest waning glacial activity provided the main source of sediment to the lake until 11 600 cal. BP. The end of the glacial activity is contemporaneous with the end of the Younger Dryas (YD; 12 900–11 600 cal. yr BP, 11 000–10 000 ^{14}C yr BP). In the western USA, YD glacial advances are recognized from the central Rocky Mountains (Reasoner *et al.*, 1994; Gosse *et al.*, 1995; Menounos and Reasoner, 1997), and also in the San Juan Mountains of Colorado (Reasoner and Jodry, 2000) and Sangre de Cristo Mountains of New Mexico (Armour *et al.*, 2002).

Rhythmic clay layers and organic gyttja mixed with clastic sediments deposited from 11 600 to 11 350 cal. BP suggest a transition to autochthonous sediment production in a fairly open landscape. MS gradually decreases and reaches somewhat stable values by 11 050 cal. BP, probably indicating stabilization of the landscape because of an increase vegetation cover, while remains of *Daphnia* support evidence for increased lake productivity by 11 200 cal. BP.

The occurrence of gyttja with fine, discontinuously laminated mottled clay layers dating from *c.* 10 430 cal. BP to 8980 cal. BP may indicate cooling with renewed glacial activity upslope from LML or increased runoff, possibly as a consequence of increased summer precipitation. Increased forest density that is indicated in the pollen record suggests the latter, see below. After 9620 cal. BP *Picea* macrofossils are interspersed throughout the rest of the core, indicating a greater forest density near the lake.

Reconstruction of vegetation history and moisture regimes at LML

Our vegetation reconstructions rely on a combination of pollen percentages and ratios, and plant macrofossils. The moderate size of the lake suggests that sediment would contain approximately equal proportions of local and regional pollen (Jacobson and Bradshaw, 1981). Plant macrofossils, however, are entirely local. This combination has allowed us to comment on local as well as wider regional vegetation change.

Low pollen concentrations during LML-1 time suggest that the landscape around LML was relatively open. Initial taxa around the lake were probably herbs and shrubs, including *Artemisia*, Cheno-ams, *Ambrosia*, Rosaceae (cf. *Dryas*), *Alnus* and *Salix*, existing as an alpine tundra vegetation. While *Picea* is the most prominent arboreal pollen type during this time, low pollen concentrations and lack of macrofossils suggest that trees were not present around LML.

Maher (1972) used the S/P (*Picea* to *Pinus*) pollen ratio to reflect changes in *Picea* forest density in the San Juan Mountains. During the lateglacial the S/P ratio peaks above the mean and *Picea* macrofossils appear suggesting that the *Picea* forest density was high and that treeline was close to the lake. The appearance of *Picea* (11 200 cal. BP) may indicate warming temperatures, dry conditions or simply that glacial melting created a new habitat for *Picea*.

Pinus edulis, which today grows in the lower foothills of the San Juan Mountains at ~1700–1800 m elevation (Komarek, 1994), also increases *c.* 11 095 cal. BP. It is highly unlikely that *P. edulis* grew near the lake based on modern tolerances and lack of macrofossils. Therefore, the increase in the lateglacial reflects expansion at lower elevations and consequent upslope movement of the pollen to the lake. The occurrence of *P. edulis* has been used as an indicator for summer rainfall and could be a good proxy for monsoonal activity (Davis, 1994; Petersen, 1985, 1988). An abrupt increase in diploxylon *Pinus* pollen (either *P. ponderosa* (ponderosa pine) or *P. contorta*) occurs *c.* 10 160 cal. BP. Other studies (ie, Anderson, 1989, 1993; Weng and Jackson, 1999) documented an expansion of *P. ponderosa* in the early Holocene. Because the distribution of *P. ponderosa* and summer monsoonal precipitation in the Southwest coin-

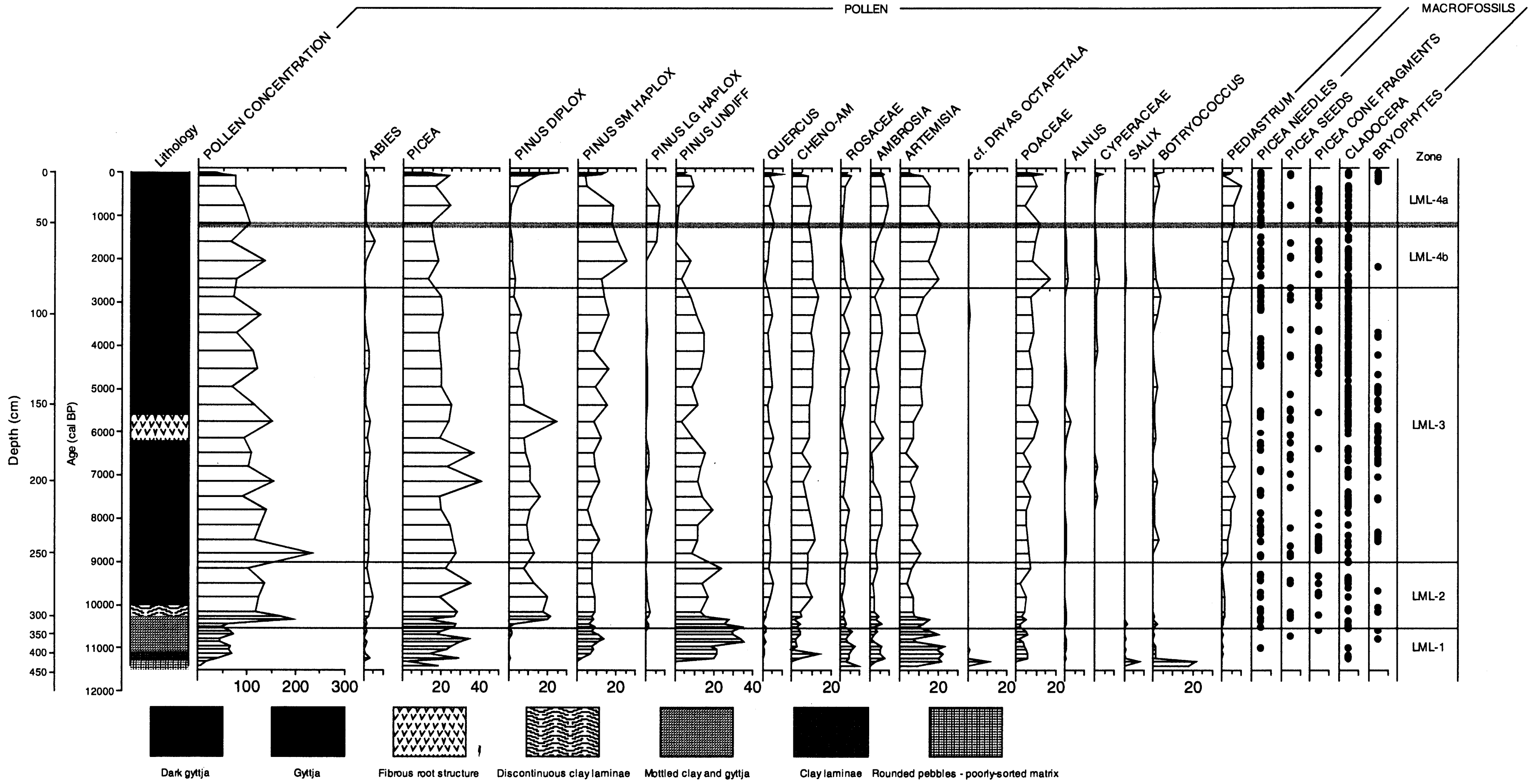


Figure 6 Little Molas Lake, Colorado, pollen and macrofossil diagram

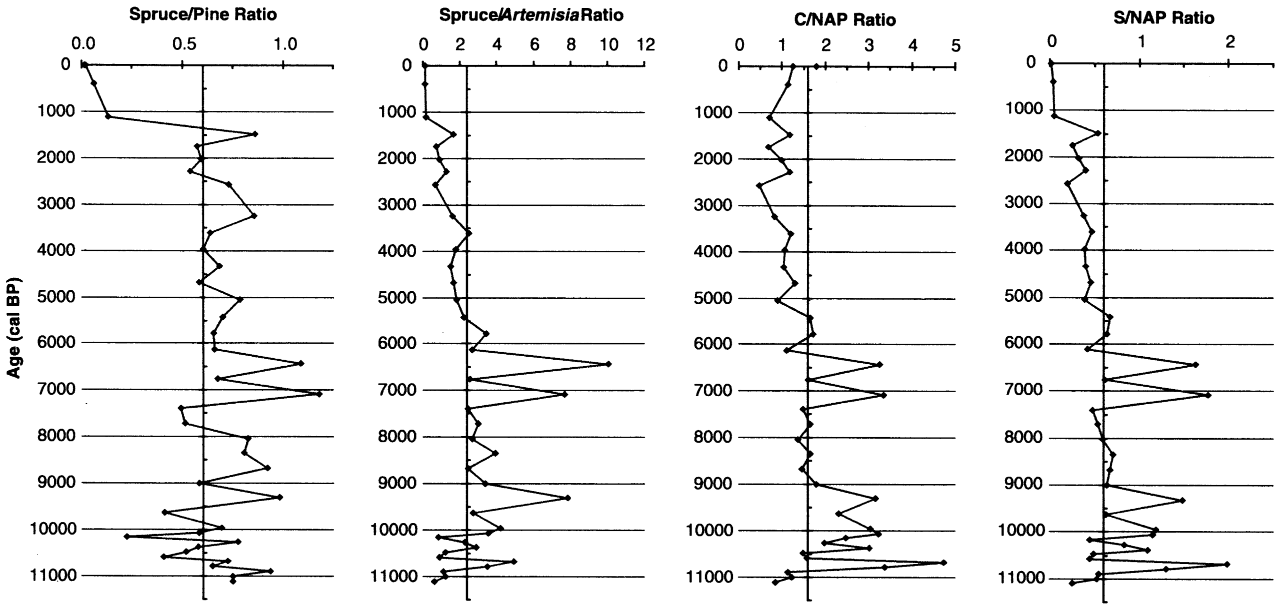


Figure 7 Pollen ratio diagrams from Little Molas Lake, San Juan Mountains, Colorado. C, conifer pollen sum; NAP, non-arboreal pollen sum solid lines, pollen zone boundaries, dotted lines, pollen subzone boundaries

cide, its expansion may be a better indicator of the arrival of the monsoon to this part of Colorado.

High total *Pinus* and pollen concentrations subsequent to *c.* 9000 cal. BP suggest that forests were dense. Assuming diploxylon *Pinus* is *P. ponderosa*, expansion of the tree's range at lower elevations is indicated. It is possible that *P. contorta* (another diploxylon pine grain), which today occurs both in the montane and subalpine (Komarek, 1994), expanded as well. Our data cannot settle this question. However, the decline in *Artemisia* with the increase in Cheno-ams probably reflects warming temperatures or drier conditions from the lateglacial into the early Holocene, which would not have favoured *P. contorta*.

S/P ratios are generally high throughout much of the early Holocene. S/P ratios correlate with S/A ratios until 6200 cal. BP, after which the S/A ratio falls below the mean and probably suggests a change in the depositional environment (Maher, 1972). One depositional change may have been caused by a shallow lake phase indicated in part by an increase in bryophyte remains at 6200 cal. BP. Lower surface area of the lake at this time may have decreased pollen input from the atmosphere, while increasing representation of pollen by stream input. Drier conditions are also indicated by an increase in NAP (*Artemisia* and Poaceae), a decline in undifferentiated *Pinus* and *Abies*, an increasing fire event frequency (Figure 5), and a decline in the sedimentation rate (Figure 3). A similar shallow lake phase from 6600 to 4230 cal. BP was also identified on the Kaibab Plateau (Weng and Jackson, 1999). The lower lake level at LML may be a local expression of long-term drought conditions across the Southwest, and should be investigated at additional locations.

Between 2650 and 1250 cal. BP a decline in *P. contorta* and/or *P. ponderosa* and the increase in *P. edulis* pollen percentages suggest that the latter may have expanded at the expense of the former at elevations lower than LML. Expansion of *P. edulis* has been ascribed to both summer (Petersen, 1985) and winter (Anderson *et al.*, 2000; Metcalfe *et al.*, 2000; Holmgren *et al.*, 2003) precipitation. We consider the expansion of *P. edulis* to reflect increased effective moisture in general and possibly winter precipitation, until after *c.* 1500 cal. BP, when the S/NAP ratio declines, indicating a potentially more open forest. The C/NAP peaks above the mean (1.6) just after AD 1950, which probably results from anthropogenic planting of *P. contorta* near the lake (Binkly, 2003).

Fire history at LML

Several recent studies have documented that centennial-scale fire return intervals are characteristic of spruce-fir forests in the Rockies. Infrequent stand-replacing fires have dominated the fire regime in these forests over the past ~750 to ~450 years; whereas, evidence of small, non-lethal surface fires is limited to the post-EuroAmerican period (Veblen *et al.*, 1994; Kipfmueller and Baker, 2000; Sherriff *et al.*, 2001). Unlike the lower elevation *P. ponderosa* montane forests of the Rockies where fire frequency has declined during the twentieth century (Kipfmueller and Baker, 2000; Veblen *et al.*, 2000), the subalpine forests have shown a slight increase in fire frequency from the nineteenth to twentieth centuries from every ~170 years to every ~130 years (Kipfmueller and Baker, 2000; Sherriff *et al.*, 2001)

Long *et al.* (1998) documented the importance of background charcoal, a reflection of regional fires and charcoal peaks, derived from local fires. Interpretations depend upon the changing relationship between the background and peaks component of the sedimentary charcoal record. Our analysis indicates that during the lateglacial and up to 10 500 cal. BP fire events occurred at a rate of one event per 65 years (Figure 4). This high fire frequency is uncharacteristic of the *Picea* forest that persists near LML today. We believe that this high fire frequency may have been the result of widespread regional vegetation change, with a considerable amount of dead organics distributed across the landscape as one species replaced another. Support comes from MS values, which stabilize in the sediment core and remain low after 11 050 cal. BP, suggesting that the charcoal may not result from local fire disturbance. The transition from the lateglacial to the early Holocene coincides with a doubling of the fire return interval to 130 years. The lithology during this transition indicates that the doubling may have been the result of cooler and moister conditions.

The lowest Holocene fire event frequency occurs from 4100 to 2620 cal. BP, averaging one fire every 180 years. Even so, pronounced peaks in charcoal influx occur at 3820 and 3400 cal. BP, and may be a result of extended periods of fuels

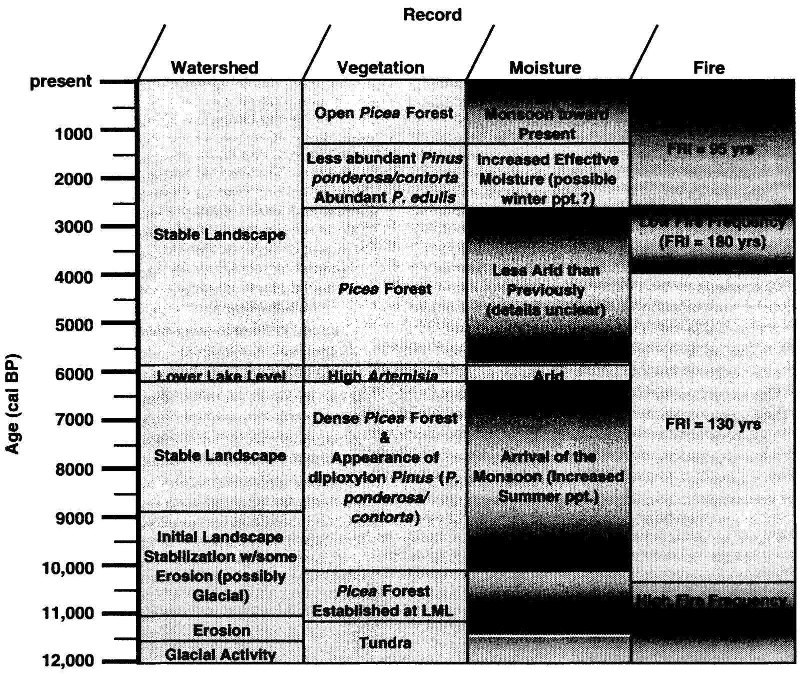


Figure 8 Summary of changes in the watershed erosion, vegetation, climate and fire history at Little Molas Lake. FRI, fire return interval

accumulation between fires with a resulting less frequent, but more intense fire regime. The general decrease in fire frequency during the Neoglacial period (Porter and Denton, 1967) is probably due to widespread moister and cooler climates in western North America at this time.

In the twentieth century pronounced peaks in charcoal influx occur at 17 cm and 9 cm that may reflect intense fires within or near the drainage basin. The only documented historical fire to burn around LML was the Lime Creek Burn of AD 1879 (Thompson, 2002) and most likely corresponds to the charcoal influx peak at 17 cm depth. The interpolated age from the ^{210}Pb chronology is AD 1910, suggesting our chronology for this part of the core may be off by several decades. But the lack of charcoal in the upper 6 cm is undoubtedly a result of late nineteenth- and early twentieth-century fire suppression and grazing (Binkly, 2003).

Late Quaternary environments of the Southern Rockies

The LML data provide an important addition to our understanding of the regional vegetation change and fire regimes in the San Juan Mountains (Figure 8). For the most part, these changes are local responses influenced by large-scale climate trends.

Full- and lateglacial palaeoecological studies from the Southern Rocky Mountains indicate that treeline was up to 500 m lower during the Pinedale glaciation (Maher, 1972, 1961; Legg and Baker, 1980; Markgraf and Scott, 1981). Highest elevation sites were glaciated, while alpine vegetation found above 3300 m today occupied areas around 2800 m elevation (Legg and Baker, 1980). Similarly, subalpine forests found between 2700 and 3300 m elevation today occupied sites below 2300 m elevation (Markgraf and Scott, 1981). High-elevation sites reflect lateglacial conditions with cold winters and increased winter precipitation and drier than present summers (Vierling, 1998), and enhanced winter storms originating in the Pacific Ocean (Markgraf and Scott, 1981). Models suggest summer precipitation was at a minimum during this period (COHMAP Members, 1988; Kutzbach *et al.*, 1998).

The LML record parallels these studies. Prior to ~11 200 cal. BP, tundra vegetation inhabited the area directly around LML, supporting the interpretations by Maher (1961) and Markgraf and Scott (1981) that conditions were colder and probably moister than present. Postglacial warming occurred after 10 700 cal. BP regionally, and after 10 570 cal. BP at LML, as shown by an increase in diploxylon *Pinus* and other arboreal pollen types.

Early Holocene records from other Southern Rocky Mountain sites indicate an upward elevational shift of many montane species (Elias *et al.*, 1991), and that temperatures and apparent elevations were higher (Petersen, 1982). *Picea* and *Abies* krummholz fragments identified by their small size and contorted annual-ring pattern in Lake Emma CO sediments indicate that the krummholz vegetation was at least 70 m higher than today throughout much of the early and middle Holocene (Elias *et al.*, 1991). Several other studies document warmer, wetter conditions from the early to middle Holocene (Andrews *et al.*, 1975; Petersen and Mehringer, 1976; Petersen, 1981), while Elias *et al.* (1991) documented periodically higher treeline between 10 900 and 3200 cal. BP.

Using deuterium (δD) of wood cellulose at Lake Emma, Friedman *et al.* (1988) suggested that summer monsoonal precipitation dominated in the San Juan Mountains in the early Holocene, but shifted to a greater mix of Pacific frontal storms and monsoons after 4400 cal. BP (Carrara *et al.*, 1991). Northward penetration of the summer monsoon into central Colorado is shown by downslope expansion of *P. edulis* during the early and middle Holocene to *c.* 4400 cal. BP (Markgraf and Scott, 1981). Vierling (1998) records warmer summer temperatures and elevated summer precipitation from 10 200 to 1800 cal. BP.

Although Antevs (1955) classified the mid-Holocene as warmer and drier than present, palaeoecological data from the Colorado mountains (Benedict, 1979) and southeastern Arizona (Martin, 1963; Mehringer *et al.*, 1967) indicate more mesic environments, suggesting the Altithermal was more complex and regionally variable. At LML, warm conditions prevailed from 10 570 to 6700 cal. BP, culminating in a shallow lake phase from 6230 to 5900 cal. BP. This falls within the mid-Holocene period of higher treeline documented by Elias *et al.* (1991). Warmer climates than today terminate *c.* 4100 cal. BP with the onset of regional Neoglaciation.

An increase in *P. edulis* and longer MFI fire event frequency implies that wetter and possibly cooler conditions existed around LML from at least 4100 until 2500 cal. BP. This pattern is noted at other nearby sites. Timberline lowering around Lake Emma reflected presumed cooling occurred after ~3100 cal. BP (Elias *et al.*, 1991). After 2800 cal. BP at Beef Pasture and Twin Lakes in the La Plata Mountains, summer and annual precipitation decreased as indicated by a decrease in *P. edulis* and a narrowing of the *Picea* zone, respectively (Petersen, 1981). From 2500 to 1500 cal. BP the Twin Lakes data indicate cooler temperatures, but drier summers (Petersen, 1981). The upward shift of *Picea* to modern elevations because of warming occurs in the Lost Park record after 1800 cal. BP, but was not noted at the La Plata Mountain sites until *c.* AD 1920 (Petersen, 1981).

Regional fire history correlations

The LML record is the first high-resolution postglacial fire history from the mountains of the Southwest. Thus, our efforts to deduce broad spatial patterns of fire and climate are hampered by the present paucity of records. However, comparison of the LML record with other high resolution records from winter-wet, summer-dry regions of California's Sierra Nevada and the Pacific Northwest, and the lower-resolution fire-history records of the southern Colorado Plateau demonstrate similarities as well as differences.

The subalpine Siesta Lake record from the Sierra Nevada indicates that fire frequency was high from 13 500 to 11 000 cal. BP and from 10 000 to 9500 cal. BP (Brunelle and Anderson, 2003). At LML fire event frequency was highest from 11 400 to 10 500 cal. BP. The difference in timing between the two locations may have many causes, including local glacial histories, proportions of seasonal precipitation and potential errors in chronology. However, the general coincidence of higher fire frequencies at the beginning of the Holocene suggests broader, regional connections, such as the influence of the solar insolation maximum and climate controls originating in the Pacific Ocean.

Recent studies (Whitlock *et al.*, 2003; Brunelle *et al.*, 2005) have suggested that seasonal distribution of precipitation influences fire regimes. For example, the summer-dry sites of the Klamath Mountains, Coast Range and Northern Rocky Mountains all exhibit high fire frequency in the early Holocene; whereas, the summer-wet sites of the Northern Rocky Mountains experience lower fire frequencies. The LML region shows a pattern similar to the summer-dry sites of the Pacific Northwest, yet it is well within the area influenced by the developing summer monsoon at that time (Friedman *et al.*, 1988). This suggests that factors other than climate, such as biomass accumulation rates or major changes in vegetation, may have influenced fire history. A decline in fire event frequency at the LML site coincides with an increase in *P. ponderosa* (large diploxylon *Pinus* grains) indicating an increase in monsoonal precipitation.

Seasonality of solar insolation in the early Holocene was greater than today, leading to warmer summers and cooler winters but, at some sites, intensely dry summers as well (Whitlock and Bartlein, 1993). Spatial variations in precipitation in the western USA are largely controlled by the polar jet stream, Pacific subtropical high and subtropical ridge (Mock and Bartlein, 1995); hence, it is not unexpected to see correlations between studies in the Sierra Nevada, the San Juan Mountains and elsewhere. For instance, the low-resolution charcoal records from the Kaibab Plateau of Arizona (Weng and Jackson, 1999) are in general agreement with the high-resolution charcoal records from LML and Siesta Lake, showing that the lateglacial was a time of high fire event frequency. Although the relative timing is unclear, fire may have facilitated vegetation change on the Kaibab Plateau, from tundra to spruce and to ponderosa pine. The fact that records as distant as British Columbia show high fire event frequencies during the lateglacial (Hallett and Walker, 2000; Hallett *et al.*, 2003) attest to similar controls on burning in these transitional forests.

Fire event frequencies at LML peak during the middle Holocene from *c.* 7000 to 5800 cal. BP, while greater centennial-scale fire variability occurs in the Siesta Lake (SL) record from 6400 to 3000 cal. BP and suggests a long-term increase in effective moisture, which after 3000 cal. BP caused a decrease in fire frequency at SL. The LML record documents a decrease in fire frequency from 4100 to 2540 cal. BP that reflects increased moisture during the Neoglacial. The onset of changing fire frequencies at LML is delayed from the similar change that occurred in the Siesta Lake record, possibly as a result of the greater influence of the monsoon at the LML site.

Fire event frequencies during the late Holocene exceed any other period since the lateglacial at LML. A maximum of 9 events/1000 years is recorded between *c.* 2800 and 1800 cal. BP. The charcoal and pollen record from Beef Pasture in the neighbouring La Plata Mountains also reflects increase fire frequency after 2800 cal. BP. Pollen data suggest this coincides with expansion of grasslands and drier conditions at La Plata sites, and increase in *Artemisia* and grass at LML. These events suggest cooler and drier conditions throughout southwestern Colorado at this time.

Conclusions

Research from LML sediments helps clarify two questions in the palaeoenvironmental history of the San Juan Mountains of Colorado: what was the history of deglaciation, and what has been the long-term fire and vegetation history of the region? On the former, data from LML confirm an earlier age for deglaciation than originally assumed. On the latter, the LML data provide the first documentation of the character of fire frequency in the subalpine zone of the southern Rocky Mountains.

Atwood and Mather's (1932) moraine maps document the maximum extent of Pinedale (Wisconsin) glaciation in the San Juan Mountains, an age confined between 40 000 and 11 400 cal. BP (Leonard, 1984). Minimum confining ages on deglaciation based on basal sediments of glacially formed lakes suggest ice-free conditions above 3730 m elevation by 10 000 cal. BP (Carrara *et al.*, 1991); with north-facing cirques also deglaciated before ~10 000 cal. BP (Andrews *et al.*, 1975). The minimum confining age for LML is older than the other studies. This may be because LML was part of an independent valley glacier system with a generally south-facing aspect; whereas Lake Emma, although in a south-facing cirque, had an ice field centred directly over it; and the other lakes from the study by Andrews *et al.* (1975) were in north-facing cirques. Regional deglaciation may have been contemporaneous throughout the San Juan Mountains; however, aspect and complex glacial systems dictated temporal variations in local deglaciation.

Comparison of our fire history record with others for the lateglacial in western North America provides support for two hypotheses. Generally higher fire event frequencies during the lateglacial–early Holocene transition are linked to greater seasonality, perhaps with more frequent ignition source from monsoon storms. But this time period also witnessed landscape-scale changes in plant communities, which undoubtedly provided high fuel loads as antecedent species were replaced by new arrivals. The results of high-resolution pollen studies for this time period may provide greater resolution on the relative influence of these two factors.

During the Holocene, fire event frequency never reached the levels of the lateglacial transition. This could provide support for the fuel load hypothesis, or it could be a result of the relatively infrequent fires of spruce–fir forests of the subalpine zone. Our estimates of Holocene fire return intervals vary from *c.* 130 to 180 years. These estimates are reasonable given standage studies that suggest return intervals of 35–202 years (Veblen *et al.*, 1994; Alington, 1998; Kipfmueller and Baker, 2000; Sherriff *et al.*, 2001). The longest return interval (~ 180 years) at LML occurred at the beginning of the Neoglacial, *c.* 4100–2600 cal. BP.

Overall, examining multiple proxies from the LML core has provided a more complete documentation of the changes within the region. For example, it is doubtful that the Neoglacial would have been recognized without the aid of the charcoal record. The use of the pollen ratios in this type of terrain has proven invaluable. The comparisons that the ratios provide among the various taxa show trends that based on the pollen percentages alone are ambiguous. The increase in large diploxylon pine pollen thought to represent *P. ponderosa* suggests that the monsoon may have been important to this region as early as 10 400 cal. BP. But the lack of major changes in the *P. edulis* pollen throughout much of the record has made it difficult to determine the dynamics of precipitation at lower elevations. The late Holocene expansion of *P. edulis* that occurred contemporaneously with lower fire frequencies may indicate greater winter precipitation during the Neoglacial period in the San Juan Mountains.

The response of the environment to changes in fire regimes has implications for forest management. Because fire suppression practices have been in place since the late nineteenth century in the San Juan Mountains, and planting of 'exotic' trees has occurred near LML, it is difficult to study modern forests there to understand natural fire regimes. Therefore, palaeoecological studies such as the one presented here serve as an important tool for understanding natural fire regimes at high elevations. We cannot say, however, whether fire suppression has affected high-elevation subalpine forests of the region, since our reconstructed fire event frequencies are less than or equal to modern estimates from stand-age studies (Buechling and Baker, 2004).

Acknowledgements

We thank Allison Bair and Mark Daniels for assistance with fieldwork; Craig Allen (USGS) for providing logistical and financial support; Donald Rodbell (Union College) for use of the coulometer; Ros Wu (US Forest Service) for information on historical fires, Richard Ku (USC) for providing the ^{210}Pb and ^{137}Cs profile; and Douglas Hallett and Julio Betancourt for very helpful discussions. We also thank two anonymous reviewers for their comments, which improved the manuscript. Funding came from Cooperative Agreement 1455-0009-94-1069 between the USGS-BRD and Northern Arizona University (NAU) to RSA; and Research Grant 7290-02 from the Geological Society of America and Grants-in-Aid of Research from Sigma Xi to JLT. Laboratory of Paleoecology Contribution # 88.

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