A 20,000-YR-OLD RECORD OF VEGETATION AND CLIMATE FROM LOWER RED ROCK LAKE, CENTENNIAL VALLEY, SOUTHWESTERN MONTANA

by

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A thesis submitted in partial fulfillment
of the requirements for the degree

of

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in

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ABSTRACT

A ca. 20,000-yr-old sediment core from Lower Red Rock Lake (LRRL) in the Centennial Valley of southwest Montana was obtained to reconstruct the vegetation, climate, and environmental changes during and following the late-Pinedale Glaciation in the northern Rocky Mountains. The base of core LRRL 06P49 consisted of inorganic silt and clay, deposited when a large glacial lake occupied the eastern Centennial Valley. The glacial lake receded during the late-glacial period when its western outlet stabilized. Prior to 17,000 cal yr BP, high pollen percentages of *Juniperus*, Poaceae, Asteraceae, and other herbs as well as low pollen accumulation rates suggest cold dry conditions. The sparsely vegetated landscape at LRRL is consistent with paleoclimate model simulations that show southward displacement of the jet stream and a strong glacial anticyclone during the full-glacial period. Between 17,000 and 10,500 cal yr BP, increases in *Picea* and *Abies* pollen percentages suggest a shift to subalpine parkland and warmer conditions than before as result of the northward shift of the jet stream and increasing summer insolation. From 10,500 to 7100 cal yr BP, pollen percentages of *Picea* and *Abies* decreased and those of xerophytic taxa (e.g., Chenopodiaceae and *Pseudotsuga*) increased, suggesting development of steppe and open forest. Warmer drier conditions in the early Holocene were likely a response to increased summer insolation and a strengthened Pacific subtropical high-pressure system. From 7100 to 2400 cal yr BP, cooler and moister conditions at LRRL, driven by decreasing summer insolation, led to the expansion of high-elevation conifers, steppe, and wetlands. Increases in *Picea* and *Abies* pollen percentages after 2400 cal yr BP indicate further closing of forests at high elevations and even cooler and wetter conditions than before. Examination of the first arrival of *Pseudotsuga* in pollen records throughout the region shows that its arrival was later at sites on the Atlantic side of the Continental Divide as compared to sites on the Pacific side. The geographic pattern suggests that the Continental Divide posed a topographic or climate barrier in the late-glacial period, delaying the migration of *Pseudotsuga menziesii* from glacial refugia.

INTRODUCTION

Geologic and paleoclimatic data from the northern hemisphere document large changes in global climate over the last 21,000 years, as the earth transitioned from a full-glacial environment to the present-day interglacial environment (Thompson et al, 1993). Following the last glacial maximum (LGM), ice sheets disappeared, forests were altered compositionally and spatially, and several genera of large mammals went extinct (Grayson and Meltzer, 2003; Thompson et al., 1993). Since the LGM, global climate has warmed on the order of 4 to 7 °C, according to paleoclimate models and proxy data (Jansen et al., 2007). Understanding past climates and the conditions that give rise to large environmental change is important to modern initiatives that aim to forecast future climate change (IPCC, 2007; Kutzbach et al., 1993), and understanding the biotic response to climate during such transitions is important for predicting the ecological impacts and feedbacks of future climate change.

In the Northern Rocky Mountains, the full-glacial landscape was dominated by the presence of the Cordilleran Ice Sheet at high latitudes and alpine glaciers at high elevations in mountain ranges (Pierce, 2004). Existing pollen, insect, faunal and geologic evidence suggests cold and dry conditions in the Northern Rocky Mountain region at the LGM (Thompson et al, 1993), although the current network of paleoecologic sites dating back to the LGM is sparse for this region. Two records of this age are Grays Lake in southeastern Idaho (Beiswenger, 1991) which extends to at least 60,000 cal yr BP and a 20,000 yr record from Hedrick Pond in Grand Teton National Park (Whitlock, 1993), which will both be compared to the LRRL record in this paper.

This thesis describes the vegetation and climate history of the Centennial Valley based on pollen and lithologic analyses of a 20,000-year-old sediment core from Lower Red Rock Lake. Lower Red Rock Lake is located in Red Rock Lakes National Wildlife Refuge (44° 37' 49" N, 111° 50' 14" W; 2015 m elev.) (Figure 1) and managed by the U.S. Fish and Wildlife Service. The refuge lies at the eastern end of the Centennial Valley of southwest Montana, a tectonically active fault-created basin 50 km west of Yellowstone National Park (YNP), and is considered part of the Greater Yellowstone Ecosystem.

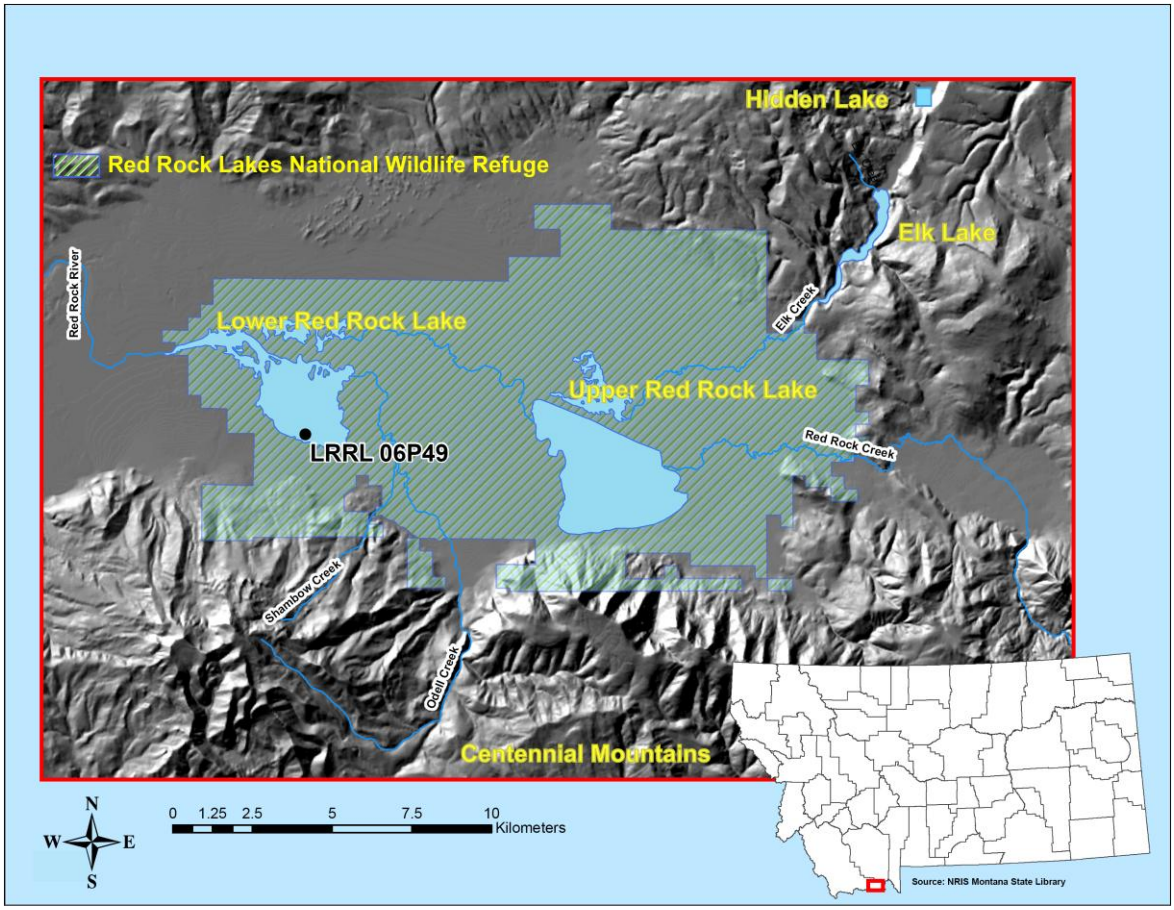


Figure 1. Location of core LRRL 06P49 in Lower Red Rock Lake, Centennial Valley, Montana. Inset shows the location of the eastern Centennial Valley as it relates to Montana county divisions.

The objectives of this thesis were to answer the following questions: 1) What were the climate conditions and vegetation during the last glacial maximum and how has the vegetation changed during the late-glacial period and Holocene in the eastern Centennial Valley? 2) How does vegetation history compare with other sites in the Northern Rocky Mountain region? 3) How does the inferred climate history of Lower Red Rock Lake contribute to our understanding of large-scale controls of climate?

Lower Red Rock Lake is an ideal site for this investigation because it was unglaciated during the full-glacial period, yet it was within close proximity to alpine glaciers in the Centennial Mountains and the glacial complex of Yellowstone National Park. Thus, the pollen record from Lower Red Rock Lake describes the vegetation during the full-glacial period and the ecological changes that ensued during deglaciation and the Holocene. The vegetation reconstructions from Lower Red Rock Lake and other sites in the Northern Rocky Mountains provide clues into the biotic response to climate and the development of the modern landscape.

SITE DESCRIPTION

Physical Setting

The east-west-trending Centennial Mountains, which rise to elevations over 3000 m, border the Centennial Valley on the south, and the north-south trending Gravelly and Snowcrest ranges lie to the north (See fig. 1). During the late Cenozoic Era, uplift associated with the Yellowstone hotspot occurred. The Centennial Mountains formed as a combination of this uplift and extensional fault mechanics (Pierce and Morgan, 2009; Sonderegger et al., 1982). This is evidenced by an active normal fault on the southern margin of the valley (Witkind and Prostka, 1980) which has accumulated about 10 m of offset in the last 15,000 years (Petrik, 2008). Thick deposits of Huckleberry Ridge Tuff from the Yellowstone volcanic field ca. 2 million years ago were laid down in the Centennial Valley, implying that the mountains were not high enough to block this ash flow from flowing into the valley. The Centennial Mountains had risen to sufficient height to block passage of the northward flowing Mesa Falls ash flow (ca. 1.2 million years ago) from the Island Park caldera (Sonderegger et al., 1982; Christiansen, 1982).

Maximum position of late-Pinedale outlet glaciers from the Yellowstone glacial complex is evidenced by outermost Pinedale moraines which range in age from about 18.8 to 14.6 ^{10}Be yr BP (Licciardi and Pierce, 2008). In addition to the Yellowstone glacier system, other nearby mountain ranges supported alpine glaciers during the late-Pinedale Glaciation. Ages of the inner and outer Jenny Lake moraines of the Teton Range are about 14.6 to 13.5 ^{10}Be yr BP, whereas moraines in the Wind River Range

yield ages which are > 4,000 years older on average than those in Yellowstone and Grand Teton National Parks, with a range of about 24.7 to 18.0 ^{10}Be yr BP (Licciardi and Pierce, 2008; Gosse et al., 1995a,b). Glaciers in the Centennial Mountains reached the edge of the valley floor (Locke and Smith, 2004). Studies suggest that the eastern Centennial Valley was once a large, deep (~20 meters deep) lake, Pleistocene Lake Centennial. This lake formed as a result of a late-Pleistocene-age landslide that blocked Red Rock River from flowing northeastward to the Madison River (Sonderegger et al. 1982). Such landslides dammed Elk, Hidden, Cliff, Wade, Hidden, Otter, and Goose lakes to the northeast. Late-Pleistocene alluvial fans were built to the edge of this deep lake and locally built to lower shorelines as the lake receded. As a result of lake recession, present-day Upper and Lower Red Rock Lakes were formed. The present lakes are separated by alluvial fans which pre-date the Pleistocene lake (Pierce, Unpublished data).

At present, Lower Red Rock Lake has an average depth of 1.2 m (U.S. Fish and Wildlife Service, 2008) and is surrounded by marshland and fen. Holocene alluvial deposits are present along the main drainages, and Pleistocene and Holocene eolian sand dunes are found on the north side of the valley (Witkind and Prostka, 1980) which may be reworked from lacustrine beach and lake sediments of Pleistocene Lake Centennial. To the north of Lower Red Rock Lake, the foothills of the Gravelly Range are made of Tertiary volcanic deposits, and to the southeast of Lower Red Rock Lake, exposed bedrock in the Centennial Mountains is mostly Paleozoic carbonate rock. Directly south of Lower Red Rock Lake, the Centennial Mountains are composed of Cretaceous shale, mudstone, conglomerates and Tertiary volcanics. Late-Pleistocene sediments overlie the

basin fill of the eastern Centennial Valley (O'Neill and Christiansen, 2004; Witkind and Prostka, 1980).

Climate

The Centennial Valley is currently influenced by two large-scale climate patterns that affect the seasonal distribution of precipitation: 1) westerly flow directs Pacific storm tracks up the Snake River Plain to the valley in winter and late-spring, 2) storms track along the jet stream from the Aleutian low-pressure system, bringing moisture in winter; and extremely cold and dry conditions arise in the valley when arctic continental polar air shifts southward (Mock, 1996). Mean temperatures in Lakeview, MT at the southwest boundary of the refuge are highest in July, averaging 14.8°C, and January temperatures average -11.6°C.

Average annual precipitation for Lakeview, MT is about 50 cm. May and June are the wettest months when Pacific storms moving up the Snake River Plain are intercepted by the east-west-trending Centennial Mountains and the Yellowstone Plateau (U.S. Fish and Wildlife Service, 2008; Mock, 1996). Average precipitation for May and June are 6.4 cm and 7.2 cm, respectively, and precipitation is suppressed in summer when the northeastern Pacific subtropical high pressure system expands and shifts north of its winter position. Monthly precipitation for both July and August averages 3.7 cm. January precipitation averages 3.5 cm (Western Regional Climate Center, 2009. http://www.wrcc.dri.edu).

Vegetation

Common and scientific names for plants are based on a list of local vegetation in Red Rock Lakes National Wildlife Reserve (US Fish and Wildlife, 2009), and follow the Integrated Taxonomic Information System (http://www.itis.gov) for accepted taxonomic order. The modern vegetation of the Centennial Valley is arranged along an elevational gradient. Lower Red Rock Lake (approx. 2015 m elev.) supports aquatic species, such as Richardson's pondweed (*Potamogeton richardsonii),* shortspike watermilfoil *(Myriophyllum sibiricum),* and several species of sedge (*Carex spp.*) and the valley floor contains perennial grasses such as Idaho fescue (*Festuca idahoensis*) and tufted hairgrass (*Deschampsia cespitosa).* Adjacent hills (≤ 2100 m elev.) are dominated by big and threetip sagebrush (*Artemisia tridentata, Artemisia tripartita*), bunchgrass, and Idaho fescue. Riparian areas are populated with quaking aspen (*Populus tremuloides*) and willows (*Salix spp*.).

Above about 2100 m elev. are open forests of Douglas-fir (*Pseudotsuga menziesii* var. *glauca*), limber pine (*Pinus flexilis*), and Rocky Mountain juniper (*Juniperus scopulorum*) and above 2440 m elev., mountains are covered with closed forests of whitebark pine (*Pinus albicaulis*), subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and common and creeping juniper (*Juniperus communis, J. horizontalis*). Lodgepole pine (*Pinus contorta*) is present in upper-elevation forests. Upper treeline is located at about 2900 m elev., above which is alpine tundra with abundant cold-tolerant forbs. Forest composition on the north and south sides of Lower Red Rock Lake is similar, although forest cover is less dense to the north on the foothills

of the Gravelly Range, probably reflecting a local decrease in precipitation resulting from orogenic effects of the east-west trending Centennial Mountains.

METHODS

A 5-cm-diameter sediment core (LRRL 06P49) measuring approximately 8.5 m in length was obtained from Lower Red Rock Lake by members of the U.S. Geological Survey Northern Rocky Mountain Science Center in July 2006. The core was taken from a floating platform anchored near the southern shore of Lower red Rock Lake using a modified Livingstone square-rod piston coring device (Wright et al., 1984). Upon extrusion, the core (LRRL 06P49) was described in the field, wrapped in plastic wrap and aluminum foil, and then transported to cold storage at Montana State University (MSU).

Descriptions and Sampling

Cores were split longitudinally and photographed in the MSU Paleoecology Lab. The split sections were compared with field notes, and additional descriptions were made. One longitudinal half of each section was rewrapped in plastic wrap and aluminum foil and archived in cold storage, and the other half was sampled for paleoecological analyses.

Lithologic Analyses

Lithologic analyses were performed at the Montana State University Paleoecology Lab. Organic and carbonate content was estimated through loss-on-ignition analysis (LOI) at 16-cm intervals. For each determination, 1-cm^3 of sediment was dried at 90°C for 24 hours, and then ignited at 550°C for two hours to burn off organic material, and at 900°C for two hours to remove carbonates. Weight-loss after

each heating process was used to calculate percentages of organics and carbonates (Dean, 1974) and these data were used to infer changes in lake productivity through time.

Magnetic susceptibility readings were taken at 1-cm contiguous intervals using a Bartington magnetic susceptibility core logging sensor (Dearing, 1999). These measurements estimate allochthonous mineral input, and higher magnetic susceptibility values suggest increased erosion rates (Gedye et al., 2000; Thompson and Oldfield, 1986).

Pollen Analysis

Pollen analysis was undertaken to reconstruct local and regional vegetation history, which was the primary focus of this investigation. Sediment samples of 1-cm^3 were processed for pollen analysis at 8-cm intervals in the core using the method described by Bennett and Willis (2002); however, the acetolysis procedure was replaced with Schultze's procedure (Doher, 1980), which employs a solution of nitric acid and potassium chlorate to remove organic material. Each sample was exposed to Schultze's solution for a maximum of 3 minutes to ensure minimal corrosion of pollen. All pollen samples were passed through a 250 micron sieve to remove large mineral grains, and clay-enriched samples were passed through a 7 micron nitex filter to remove clays. A tablet containing a known concentration of *Lycopodium* spores was added to each sample to enable calculation of pollen concentration (grains cm^{-3}), and one drop of safranin stain was added to aid in pollen identification. Silicon oil was added to the pollen residue and

the solution was mounted on glass slides and observed at 400x magnification or 200x magnification if pollen was sparse within the sample.

Between 250 and 550 terrestrial pollen grains were identified for each sample, unless pollen concentration was exceptionally low. In this case, all grains were identified until a minimum of 200 *Lycopodium* spores were counted. Pollen grains were identified to the lowest taxonomic level possible, based on modern pollen reference slides and published pollen identification keys (e.g. Kapp et al., 2000; Moore and Webb, 1978). Diploxylon-type *Pinus* grains were assigned to *Pinus contorta* and haploxylon-type *Pinus* grains were identified as *Pinus albicaulis* or *Pinus flexilis*. *Pinus* grains without distal membranes were identified as *Pinus* Undifferentiated.

Pollen percentages of terrestrial taxa were calculated by dividing the number of grains counted for each taxon by the total number of terrestrial pollen and spores counted within the sample. Modern Cyperaceae in the Centennial Valley includes both wetland-aquatic genera (eg. *Carex*) and genera that are part of the upland vegetation (eg. *Kobresia*), and thus were included in the terrestrial pollen sum in this study. Percentages of aquatic taxa were calculated based on the total sum of terrestrial and aquatic pollen and spores, including Indeterminate grains. Indeterminate percentages were also calculated based on this sum. Pollen percentage data were divided into six zones using CONISS constrained cluster analysis (Grimm, 1987). Pollen percentages in each zone were then compared with four modern pollen studies from the western U.S. to help interpret past vegetation assemblages (Bright, 1966; Whitlock, 1993; Fall, 1994; Minckley et al., 2008). Changes in pollen percentages were the basis for vegetation

reconstruction, and a ratio of arboreal taxa to nonarboreal taxa (AP/NAP) provided information on forest cover. Arboreal taxa include the following: *Pinus*, *Picea*, *Abies*, *Pseudotsuga*-type, *Juniperus*-type, *Alnus*, *Betula*, *Salix*, *Quercus*, and *Acer*.

Pollen accumulation rates (PAR) were calculated by multiplying the pollen concentration by the sedimentation rate of each sample. PAR values for each zone were then compared with modern pollen rain studies from arctic-subarctic Canada (Ritchie and Lichti-Federovich, 1967) and the Colorado Rocky Mountains (Fall, 1992) to identify particular biomes. It should be noted, however, that Lower Red Rock Lake fluctuated in size through its history, and sedimentation rates were likely variable as a result. PAR values from LRRL 06P49, based on poorly constrained sedimentation rates may not be accurate, especially for depths >5.5 m in core LRRL 06P49, where there are possible errors in the calculated sedimentation rate associated with dating errors (these are discussed in detail later). For these depths, the pollen concentration of each sample, which is independent of the age-model, was used to aid in biome identification.

RESULTS

Chronology

The chronology for core LRRL 06P49 proved to be somewhat problematic due to the scarcity of datable terrestrial organic material. Numerous efforts at sieving sections of the core yielded little suitable material. Two age-depth models are proposed. The original chronology for Lower Red Rock Lake, Option 1, was based on the identification of Mazama ash and Glacier Peak ash layers B and G, and four of five AMS ^{14}C dates in core LRRL 06P49 (Figure 2, Table 1). Option 2 uses the ash identifications and one of the five radiocarbon dates along with a radiocarbon date from a nearby stratigraphic section (Pierce, 2009, unpublished data).

Three volcanic ash samples were submitted for electron microprobe analysis and identification to the U.S. Geological Survey Tephrochronology Lab in Menlo Park, CA. One sample could not be identified, but samples "364-366 cm" and "607.5-608.5 cm" were positively identified as Mazama ash and undifferentiated Glacier Peak ash layers B and G, respectively.

Five samples of organic material were submitted to the USGS lab which prepared samples and submitted them to Lawrence Livermore National Laboratory for AMS ^{14}C dating. One radiocarbon sample (WW6157) returned a high $\delta^{13}C$ value of -10.25, which suggests that material submitted was submergent aquatic plant material. The age determination for that sample was rejected on the basis of being erroneously old and not used in developing an age model. Because Odell Creek, which flows directly into Lower

Red Rock Lake, has a large alluvial fan that drains Paleozoic limestone, submergent aquatic plants may have incorporated ancient carbon from dissolved carbonate (Deevey et al., 1954; Shotton, 1972). Sample WW6158 also has a questionable $\delta^{13}C$ value

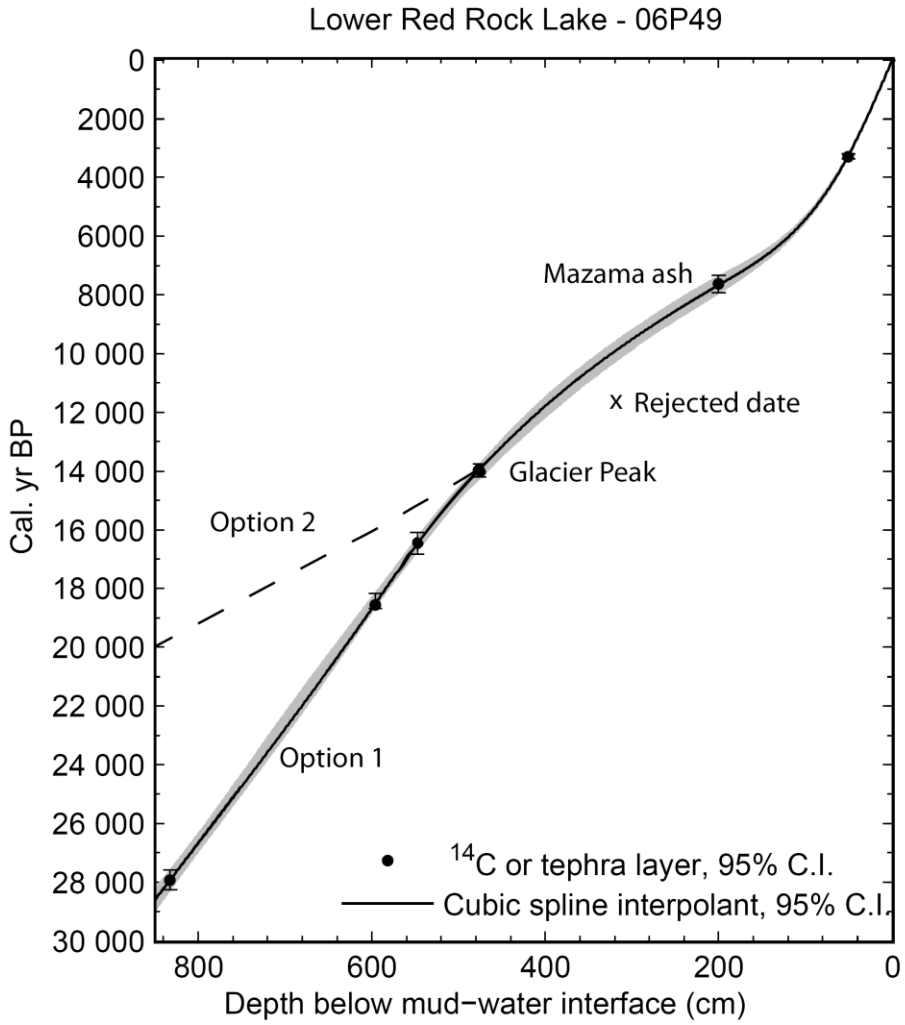


Figure 2. Age-depth model for Lower Red Rock Lake core LRRL 06P49. Black dots represent the median calibrated AMS ^{14}C age with 95% confidence interval (C.I.) (bars) and the calibrated age of known tephra. The black line is the interpolated modeled age with 95% C.I. (gray shading) based on MCAgeDepth age model program (Higuera, 2009). Option 1 (solid line) assumes that the three oldest radiocarbon dates are valid and Option 2 (dashed line) is extrapolated from Option 1 based on an independent date at the base of lake sediments from nearby stratigraphic section (Pierce, 2009, unpublished data).

(-14.32), which could also imply that the material was submergent aquatic in origin. This date fits well into the Option 1 age model however, given confidence in the Glacier Peak ash identification, and was not discarded.

Option 1 samples WW6172 and WW6173 were composed of bulk organic sediment, and their validity is also suspect. Although these samples, submitted for radiocarbon dating by U.S. Geological Survey, yielded terrestrial values for $\delta^{13}C$, they might not reflect the true age of sediment deposition. Odell Creek drains the Cretaceous Frontier Formation, which contains coal seams, and the dated bulk material could have contained ancient coal. Cretaceous coal, while producing a terrestrial $\delta^{13}C$ signature, would also add much older carbon to dated organic material, resulting in an age older than it actually is.

Prior to this study, Dr. Kenneth Pierce of USGS dated amorphous carbon from near the base of lake sediments that overlie gravels in a well exposed stratigraphic section. The gravels predate the formation of Pleistocene Lake Centennial. This section (05P37) is east of Upper Red Rock Lake, upstream of which coal is probably absent. The carbon at the base of lake sediments dates at 19,512 – 20,053 cal yr BP, and a conservative estimate would place the basal age of the lake sediments at roughly 20,000 cal yr BP. Therefore, an alternate age-model for Lower Red Rock Lake (Option 2) is also presented (See Fig. 2), and further inferences from analyses on sediments at depths greater than 5.5 m were broadly yet confidently dated at >17,000 cal yr BP.

Table 1. Uncalibrated radiocarbon dates and calibrated ages for core LRRL 06P49

Depth (cm)	^{14}C age	±	Median calibrated age (cal yr BP)[a]	2-sigma range (cal yr BP)	Lab ID[b]	Material	δ^{13}C (‰)
50-51	3075	35	3296	(3212 - 3373)	WW6741	wood	-25
232-234	N/A	150	7627[c]	N/A	364-366 cm	Mazama ash	N/A
329-331	10570	25	not used	(12400 - 12494) and (12569 - 12768)	WW6157	plant material[d]	-10.25
475.5-476	12100	100	13955	(13750 - 14177)	607.5-608.5 cm	Glacier Peak ash	N/A
546-549	13795	45	16433	(16079 - 16814)	WW6158	plant material	-14.32
594-598	15125	45	18559	(18133 - 18361) and (18458 - 18708)	WW6172	organic sediment[e]	-21.90
832	23280	90	27924[f]	27924 ± 172	WW6173	organic sediment[e]	-25.06
Section 05P37	16660	120	19783	(19512-20053)	WW5487	organic sediment	-25

[a] Ages were calibrated from CALIB 5.0.1 (Stuiver et al., 2005)
[b] WW- lab number assigned at USGS ^{14}C Laboratory; analyzed at Lawrence Livermore CAMS facility
[c] Calibrated age based on Zdanowicz et al. (1999)
[d] Sample was likely submergent aquatic plant material
[e] Sample may have been contaminated with ancient coal
[f] Age was calibrated using Fairbanks0107 calibration curve (Fairbanks et al., 2005)

Radiocarbon dates and the radiocarbon age of the Glacier Peak ash (Whitlock, 1993) were calibrated to calendar yr BP using Calib 5.0.1 (Stuiver et al., 2005). The Fairbanks calibration curve was used for the oldest radiocarbon date, WW6173, (Fairbanks et al., 2005) because Calib 5.0.1 uses INTCAL04, and the calibration curve does not extend back far enough to include this age (23,280 ^{14}C yr BP). The calibrated age of the Mazama ash (7627 ± 150 cal yr BP) was based on Zdanowicz et al. (1999).

MCAgeDepth (Higuera et al., 2009) was used to construct the Option 1 age-model (Fig. 2), and Option 2 was constructed by rejecting the three oldest dates (WW6158, WW6172 and WW6173) and using 20,000 cal yr BP (sample WW5487) as the basal age of the core. The MCAgeDepth program employs a Monte Carlo approach,

which randomly samples the probability-distribution of calibrated dates (1000 times, in this case) and uses the median of the sampling to generate a smooth spline through the dates. This study recognizes both Option 1 and Option 2 chronologies, but conservatively places the age of the base of the core at ca. 20,000 cal yr BP (Option2).

Lithology

Core LRRL 06P49 was divided into four lithologic units (Figure 3). Unit 4 (8.50 - 8.33 m depth; >17,000 cal yr BP) was composed of unconsolidated, olive gray (5Y4/2) medium sand. Magnetic susceptibility values were highest in this unit (54 cgs x 10^{-6}; all values listed in parentheses are mean values unless otherwise noted), implying an abundance of allochthonous sediment input (Gedye et al., 2000; Thompson and Oldfield, 1986). Organic and carbonate content were low (organic: 4%, carbonate: 4%) in comparison with other units, suggesting that these sediments were likely fluvial in origin, deposited by a stream draining the eastern Centennial Range before the lakes formed.

Unit 3 (8.33 - 5.61 m depth; >17,000 cal yr BP) was composed of gray (5Y5/1) to olive gray (5Y5/2) laminated clay. The contact between Units 4 and 3 was sharp, implying sudden damming of the valley and the creation of a lake. The organic and carbonate contents remained low (5% and 3%, respectively), and magnetic susceptibility decreased to 28 cgs x 10^{-6} but remained high relative to overlying units. These data

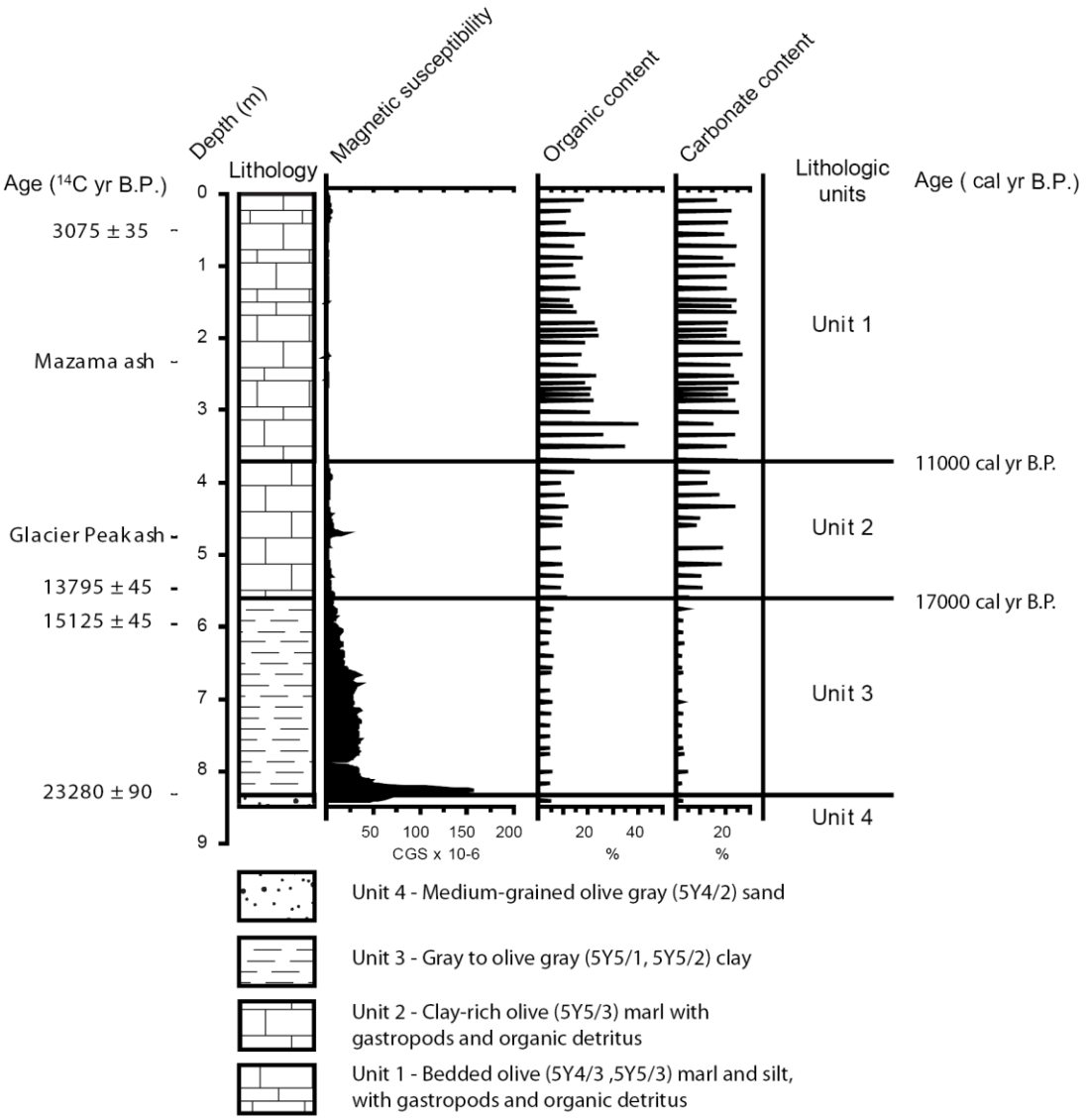


Figure 3. Lithology of core LRRL 06P49.

suggest the presence of an unproductive lake that received considerable allochthonous material from adjacent slopes and perhaps windblown dust (loess). During the deposition of Unit 3, ancient shorelines and lacustrine deposits indicate that the lake up to 20 m deep occupied the 6770 ft (2063 m) contour of the Centennial Valley.

Unit 2 (5.61 - 3.71 m depth; ≥17,000 – 11,000 cal yr BP) is calcareous olive (5Y5/3) clay with gastropod shells and inclusions of dark organic detritus. Within this unit, an ash was found at 4.75 m depth, which was later identified as Glacier Peak (See Table 1). Magnetic susceptibility values reached 20 cgs x 10^{-6} at this ash layer, but averaged 3 cgs x 10^{-6} for the entire unit. Organic content averaged 10%, and carbonate content was slightly higher than in Unit 3 (14%). Higher organic content and visible organic detritus in the form of aquatic plant fragments suggest a more productive, shallower lake than before. The lake also received less allochthonous material, as suggested by low overall magnetic susceptibility values.

Unit 1 (3.71 - 0 m depth; 11,000 cal yr BP to present) consisted of well-bedded olive (5Y4/3 and 5Y5/3) marl with minor silt and interspersed organic detritus, including numerous gastropod shells and plant detritus. Magnetic susceptibility was low for this unit, averaging 0.44 cgs x 10^{-6}, and showed a minor spike of 1.6 cgs x 10^{-6} at about 2.25 m depth at an ash layer that was identified as Mazama ash (See Table 1). Organic and carbonate content were much higher in this unit than the previous units averaging 19 and 22%, respectively. The lake attained its present level near this time, as Pleistocene Lake Centennial drained through its modern western outlet. Stratigraphic sections around the margins of Pleistocene Lake Centennial deposits reveal a buried soil layer deposited during the deposition of this unit (Pierce, pers. comm., 2008), and may suggest a period of low lake levels, although there is no obvious evidence of disconformity in LRRL 06P49. Lower Red Rock Lake and Upper Red Rock Lake are now separated by alluvial fan-forms of Odell and Teepee Creeks which predate the formation of the Pleistocene

Lake. It is likely that as water levels lowered, these two lakes formed as remnants of the once larger lake.

In summary, lithology of LRRL 06P49 suggests the following lake-level history of Lower Red Rock Lake: Unit 4 was medium sand of fluvial origin, and deposited prior to the formation of Pleistocene Lake Centennial. Unit 3 consisted of deep-water clays deposited when Pleistocene Lake Centennial was at maximum water depth and little carbonate was being precipitated, and Unit 2 records a gradual recession of this large lake with moderate carbonate deposition, which is also evidenced in ancient shoreline deposits (Pierce, unpublished data). Unit 1 represents a time of high productivity in the lake with high carbonate deposition, and lake level was near its present depth.

Pollen

Vegetation history of the Centennial Valley is based on the interpretation of five pollen zones (Figure 4): Zone LRRL-05, Poaceae-*Artemisia-Juniperus*; Zone LRRL-04, *Pinus albicaulis-Picea-Abies-Artemisia*; Zone LRRL-03, which was divided into subzones LRRL-03a and LRRL-03b based on a shift from *Artemisia-Pinus-Abies* (LRRL-03b) to *Artemisia-Pinus-Pseudotsuga* (LRRL-03a); Zone LRRL-02, Poaceae-*Artemisia-Pinus-Pseudotsuga*; and Zone LRRL-01, Poaceae-Cyperaceae-*Artemisia-Pinus-Abies-Pseudotsuga*. All percentages are listed as zone means unless otherwise noted.

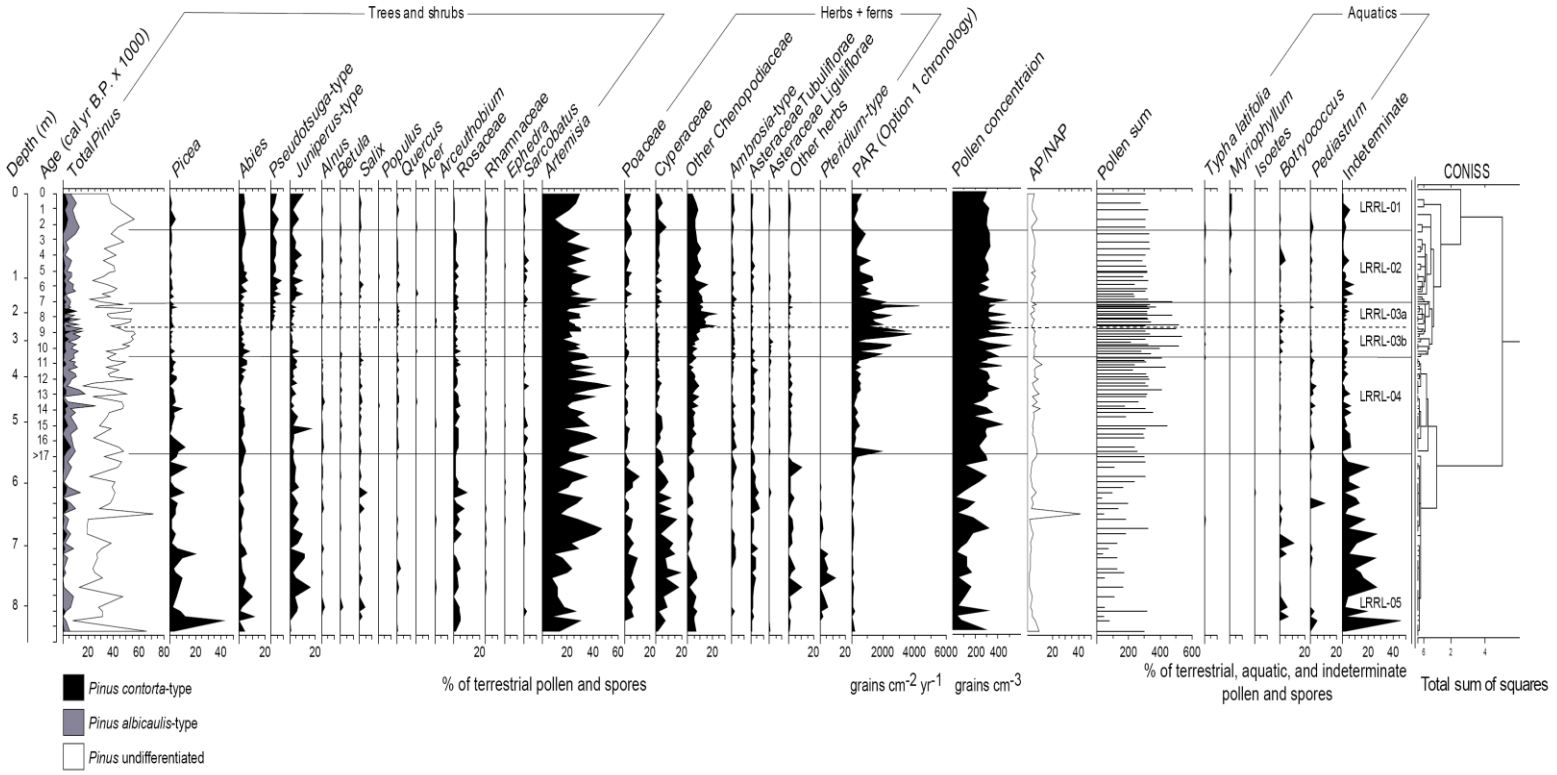


Figure 4: Pollen percentages of selected taxa, total pollen accumulation rates (PAR), pollen concentration, and AP/NAP, from core LRRL 06P49, Lower Red Rock Lake

Zone LRRL-05 (8.41-5.55 m Depth; ca. >17,000 Cal yr BP)

Zone LRRL-05 is characterized by high percentages of *Pinus* (mean value of 33%), with *Pinus albicaulis*-type (3%) dominating over *Pinus contorta*-type (1%), and *Picea* values averaging 7%. *Abies* was present in small amounts (3%), as well as *Alnus* (0.4%) and *Salix* (1%). *Artemisia* (22%), *Juniperus*-type (5%), and Cyperaceae (8%) were all present in moderate to high abundances, and Poaceae (5%), Rosaceae (3%), Asteraceae Tubuliflorae (3%) and Other herbs (2%) were at their highest of the record. "Other herbs" includes *Thalictrum*, Apiaceae, Caryophyllaceae, *Eriogonum*, other *Polygonum*, *Rumex*, *Galium*, Onograceae, Fabaceae, Urticaceae, and *Phlox*-type. *Sarcobatus* (1%), Other Chenopodiaceae (3%), and *Ambrosia*-type (1%) were present in low averages. *Pteridium*-type spores were well-represented in this zone with percentages of up to 12% (avg. 2%). *Betula*, *Quercus*, *Arceuthobium*, Asterceae Liguliflorae, Rhamnaceae, and *Ephedra* were present in small amounts (< 1%). Terrestrial pollen accumulation rates (PAR) based on chronology Option 1 were extremely low, averaging 110 grains cm^{-2} yr^{-1} (about 440 grains cm^{-2} yr^{-1} for Option 2). Pollen concentration was also low relative to other zones, averaging 4420 grains cm^{-3}. *Botryococcus* (1.3%), *Typha* (0.1%), *Myriophyllum* (0%), and *Pediastrum* (0.8%) were poorly represented.

Zone LRRL-05 pollen percentages were similar to modern pollen samples from alpine tundra (Whitlock, 1993; Fall 1994; Minckley et. al, 2008,) based on relatively high percentages of Poaceae (5%), herbs (2%), Asteraceae Tubuliflorae (3%) and Cyperaceae (8%). *Artemisia* values were higher in Zone LRRL-05 (22%) than modern values from alpine tundra in the YNP region (Whitlock, 1993). Modern samples from the Wind River

Range (Juniperus >3%) and Yellowstone National Park (YNP) (*Juniperus* >1%), have lower values for *Juniperus*-type pollen than LRRL 05 (5%). Pollen percentages match well with alpine tundra in a study of western US modern pollen rain by Minckley et al. (2008), although the authors found more Cupressaceae pollen in alpine tundra (≥20%) than in the LRRL fossil samples. In their study, four other genera, in addition to *Juniperus*, comprised Cupressaceae. The PAR in LRRL-05 (Option 1, 110 grains cm^{-2} yr^{-1}; Option 2, 440 grains cm^{-2} yr^{-1}) were within the range of modern PAR values from tundra (5-500 grains cm^{-2} yr^{-1}), which implies a sparsely vegetated landscape (Fall, 1992; Ritchie and Lichti-Federovich, 1967).

The pollen data suggest a period of sparse vegetation cover with rare *Pinus albicaulis, Picea, Abies, and Juniperus* and *Artemisia*, Poaceae, Cyperaceae, and other herbaceous taxa growing near the lake and lower slopes. Cyperaceae pollen in this zone was likely from sedges that tolerate cold conditions (eg. *Kobresia simpliciuscula*) (Vizgirdas, 2007) as opposed to the abundant *Carex spp.* which grow in wetlands near the lake at present. *Pteridium aquilinum*, which grows on present-day alpine talus slopes (Bright, 1966; Dorn, 1984), was also present. In summary, the landscape was sparsely vegetated and similar to modern alpine tundra with herbs, shrubs, and scattered cold-tolerant trees.

Zone LRRL-04 (5.55-3.46 m Depth; ca. 17,000-10,500 Cal yr BP)

In zone LRRL-04, Total *Pinus* was high (38%) with haploxylon-type *Pinus* more abundant (7%) than diploxylon-type (2%). *Picea* pollen decreased to 3%. Pollen of *Abies* remained at about 3%, and pollen of *Alnus* (1%) and *Salix* (1%) appeared throughout this

zone. *Quercus* was present with an average of 1%. *Juniperus*-type (4%) remained relatively high, and percentages of Poaceae (2%) and Cyperaceae (2%) decreased. Percentages of *Sarcobatus* (1%) and Other herbs (2%) remained low, and those of Other Chenopodiaceae (5%) rose. Asteraceae Tubuliflorae decreased from zone LRRL-05 to 2%. *Artemisia* percentages were high (30%) with a slight increase towards the top of the zone, and *Ambrosia*-type percentages were low at 1%. *Acer, Betula, Arceuthobium,* Rhamnaceae, *Ephedra,* Asterceae Liguliflorae pollen and *Pteridium*-type spores were rare. Values of aquatic pollen and spores in zone LRRL-04 were similar to those in zone LRRL-05. *Typha* averaged 0.1%, *Myriophyllum* was at 0.1%, *Botryococcus* at 0.4%; and *Pediastrum* averaged 0.8%. PAR had an average of 462 grains cm^{-2} yr^{-1}, and Pollen concentrations averaged 15,107 grains cm^{-3}.

The increase in both PAR and pollen concentration in this zone suggests that the landscape was becoming more vegetated, although the samples still fall within in the range of modern tundra vegetation for arctic-subarctic Canada (Ritchie and Lichti-Federovich, 1967). The percentage data suggest that the plant communities were dominated by *Artemisia* and herbaceous taxa with sparse *Pinus albicaulis, Picea, Abies lasiocarpa,* and probably *Juniperus communis*. Pollen percentages compare well with modern samples collected from subalpine fir, spruce, whitebark pine forest in the western US (Minckley et al, 2008) and subalpine parkland in the Wind River Range, WY (Fall, 1994).

Although the western U.S. analog indicates parkland vegetation, given that the ratio of arboreal and nonarboreal pollen remains low (AP/NAP for LRRL-05 = 5, LRRL-

04 = 6). The landscape was probably still sparsely vegetated with arboreal taxa (*Pinus*, *Picea*, and *Abies*) inhabiting higher elevations. Pollen of *Salix*, *Alnus*, and *Betula* suggest riparian areas at low to middle elevations at this time, and Chenopodiaceae likely grew at low elevations.

Zone LRRL-03 (3.46-1.66 m Depth; ca. 10,500-7100 Cal yr BP)

Zone LRRL-03 was dominated by *Pinus* (46%) and *Artemisia* (26%). The zone was divided into two subzones based on changes in the abundance of Chenopodiaceae pollen (from 7% in Subzone LRRL-03b to 14% in Subzone LRRL-03a), Cyperaceae (2% to 1%), and the first appearance of *Pseudotsuga*-type pollen (2%) in Subzone LRRL-03a. PAR values averaged 1950 grains cm^{-2} yr^{-1} and were much higher than the average PAR of zones LRRL-04 and LRRL-05. Pollen concentration was also much higher than the previous zones (34,439 grains cm^{-3}). Modern PAR analogues fall into the range of what is referred to as "forest-tundra" (Ritchie and Lichti-Federovich, 1967) in arctic-subarctic Canada and are similar to modern PAR values for *Artemisia* steppe in the Colorado Rocky Mountains (Fall, 1992). Modern pollen percentage data suggest a period of *Artemisia* steppe (Minckley et al., 2008; Whitlock, 1993), although again, *Juniperus* values (2%) were higher in LRRL-03 than modern values for steppe in YNP (Whitlock, 1993).

Subzone LRRL-03b (3.46-2.57 m Depth; ca. 10,500-8700 Cal yr BP) Total *Pinus* percentages (50%) (*Pinus albicaulis*-type, 8%; *Pinus contorta*-type, 2%) and mean PAR (1978 grains cm^{-2} yr^{-1}) increased from LRRL-04. Percentages of *Abies* (3%), *Juniperus*-

type (2%), *Alnus* (0.2%), *Salix* (0.4%), Poaceae (2%) and *Artemisia* (25%) decreased slightly or remained the same relative to zone LRRL-04. *Picea* decreased to 1% and Cyperaceae remained at 2%. *Sarcobatus* remained at 1%, but Other Chenopodiaceae percentages (7%) increased. *Ambrosia*-type pollen increased to 2%, Asteraceae Liguliflorae averaged 1%, Rosaceae averaged 2%, and percentages of Asteraceae Tubuliflorae and Other herbaceous pollen types decreased in this interval to an average of 1%. *Betula*, *Quercus*, *Arceuthobium*, Rhamnaceae, *Ephedra* pollen, and *Pteridium*-type spores were present only in trace amounts.

The pollen percentages in this subzone fall within the range of modern pollen samples from steppe in the western US (Minckley et al., 2008), YNP (Whitlock, 1993) and the Wind River Range, WY (Fall, 1994), although *Juniperus*-type (2%) was again higher in zone LRRL-03b than values for YNP and Wind River Range. PAR values (avg: 1978 grains cm^{-2} yr^{-1}) were consistent with steppe in the Colorado Rocky Mountains (Fall, 1992), and Pollen concentration averaged 42,440 grains cm^{-3}. Low *Salix* (0.4%) and *Alnus* (0.2%) values indicate a scarcity of riparian vegetation. The presence of *Typha* (0.3%) pollen suggests the development of wetlands around Lower Red Rock Lake, and a decrease in *Pediastrum* could also imply lower lake levels (Markgraf et al., 2003).

It is likely that the landscape was still fairly open during Zone LRRL-03b. *Artemisia* steppe likely existed at lower elevations, and higher PAR and Pollen concentration values than before suggest that trees were more abundant or closer to the lake. An increase in *Pinus* and decrease in *Picea* suggest a change in composition of the

forest from high-elevation forest taxa to those which currently grow at elevations below 2440 m. *Juniperus* pollen (2%) in this zone, while still higher than modern values for steppe, is likely representing more heat-tolerant *Juniperus scopulorum* rather than *J.communis*, and *J. horizontalis*, which dominated in zones LRRL-04 and LRRL-05 (Thompson et al., 2000).

Subzone LRRL-03a (2.57-1.66 m Depth; ca. 8700-7100 Cal yr BP) This subzone is identified by the first appearance of *Pseudotsuga*-type (2%) pollen along with high Other Chenopodiaceae percentages (14%). *Sarcobatus* and Poaceae pollen were present at 1%. *Abies* decreased slightly to 2%, *Picea* and *Juniperus*-type pollen remained low at 2%, and *Quercus* was present in low percentages 1%. Total *Pinus* was relatively high (43%) (*Pinus albicaulis*-type, 4%; *Pinus contorta*-type, 2%), and *Artemisia* (26%) and Rosaceae (2%) remained at similar percentages to that of Subzone LRRL-03b. *Salix* (0.2%) and *Alnus* (0.3%) were present in low abundance, and Cyperaceae and *Ambrosia*-type pollen decreased to 1%. Asteraceae Tubuliflorae and Other herbs averaged 1%, and *Populus*, *Arceuthobium*, Rhamnaceae, and *Ephedra* pollen were present in averages below 1%. PAR and Pollen concentration decreased slightly to averages of 1920 grains cm^{-2} yr^{-1} and 26,439 grains cm^{-3}, respectively.

Pollen percentages fall in the modern range of steppe for the western US (Minckley, 2008), YNP and the Wind River Range (Whitlock, 1993; Fall, 1994), although *Juniperus*-type pollen (2%) was again found in higher abundance in Subzone LRRL-03a than in the modern samples (Whitlock, 1993; Fall, 1994). PAR values are consistent with modern values from steppe in the Colorado Rocky Mountains (Fall,

1992). *Botryococcus* was present in small amounts (1.4%), *Typha* and *Myriophyllum* averaged about 0.1%, and *Pediastrum* had an average of 0.2%.

The vegetation likely featured *Artemisia* steppe at low elevations with *Pinus* and *Pseudotsuga menziesii* at higher elevations. *Pinus* accounts for most of the arboreal taxa, and haploxylon pine was likely drought-tolerant *Pinus flexilis* which grows at lower elevations and under warmer, drier conditions than *Pinus albicaulis* (Thompson et al., 2000). *Pseudotsuga* pollen is not transported long distances, so it is likely that *Pseudotsuga* was first present in the watershed at this time (Silen, 1962). In addition, the increase in Other Chenopodiaceae (14%) is consistent with open, steppe conditions, as modern genera in the area (*Atriplex* and *Chenopodium*) are highly resistant to arid and alkaline conditions.

Zone LRRL-02 (1.66-0.37 m Depth; ca. 7100-2400 Cal yr BP

This zone featured moderate percentages of *Pinus* (36%) (*Pinus albicaulis*-type, 5%; *Pinus contorta*-type, 1%) and *Pseudotsuga*-type (4%) pollen. *Abies* percentages increased slightly from zone LRRL-03 to values of 3%. Mean *Picea* was 1%. Poaceae (3%) and Cyperaceae (2%) pollen were more abundant than in the previous zone. *Juniperus* increased to 5%, *Quercus* and *Sarcobatus* were present at 1%, and Other Chenopodiaceae decreased to 9%. *Ambrosia*-type pollen, Rosaceae, and Asteraceae Tubuliflorae were present at 2%, and Other herbs totaled 1%. *Salix* (1%), *Populus* (0.1%), *Betula* (0.2%), and *Alnus* (1%) were present in low abundance. *Acer*, *Arceuthobium*, Rhamnaceae, and Asteraceae Liguliflorae pollen were extremely rare. *Typha* increased slightly to 0.4%, *Myriophyllum* increased to 0.4%, and *Pediastrum* was

just slightly higher than values in zone LRRL-03a (0.3%). *Botryococcus* decreased in this zone to 1%. PAR averaged 894 grains cm^{-2} yr^{-1} and mean Pollen concentration was 26,617 grains cm^{-3}.

PAR values were within range of values from modern *Artemisia* steppe in the Colorado Rocky Mountains (Fall, 1992). Similarly, pollen percentages matched samples from modern *Artemisia* steppe (Fall, 1994; Minckley et al., 2008). It is likely that higher elevations supported open *Pinus flexilis-Pinus albicaulis-Pseudotsuga* parkland such as they do at present. PAR values (894 grains cm^{-2} yr^{-1}) decreased from LRRL-03b (1920 grains cm^{-2} yr^{-1}) and suggest that forest cover was sparse as it is at present.

Zone LRRL-01 (0.37-0 m Depth; ca. 2400 Cal yr BP-present)

Total *Pinus* was high (44%) and of the identifiable grains, *Pinus albicaulis*-type accounted for 7% and *Pinus contorta*-type for 3%. *Abies* (4%) was also high, as were *Pseudotsuga* grains (3%), and *Juniperus*-type (6%), with a minor *Picea* component (1%). *Alnus* (0.2%), *Betula* (0.3%), *Quercus* (0.3%) and *Salix* (1%) were present in low abundance, whereas *Artemisia* (21%), Poaceae (4%), Cyperaceae (4%) and Other Chenopodiaceae (6%) were dominant. *Sarcobatus* was present at1%, and *Ambrosia*-type increased to 2%. Asteraceae Tubuliflorae was present at 2%, and Other herbs (1%) were also present in small percentages. Rhamnaceae, Rosaceae, and Asteraceae Liguliflorae were present in trace amounts. Terrestrial PAR average was low (377 grains cm^{-2} yr^{-1}). In the aquatic taxa percentages, *Typha* (0.3%) decreased from previous values, whereas *Myriophyllum* (1.4%) and *Pediastrum* (0.4%) increased. *Botryococcus* decreased to 0.2%.

Pollen percentages fall reasonably well into the modern range of percentage values from *Artemisia* steppe, although PAR values (377 grains cm^{-2} yr^{-1}) were lower than values for modern PAR in steppe for all compared studies (Fall, 1992; Davis et al., 1973; Ritchie and Lichti-Federovich, 1967). This is likely a result of poorly constrained sedimentation rates as discussed previously. Pollen concentration was similar to the previous zone and averaged 25,326 grains cm^{-3}.

Zone LRRL-01 records the development of the modern vegetation of the eastern Centennial Valley. Cyperaceae (4%) and Poaceae (4%) mark the expansion of valley wetlands and Other Chenopodiaceae (6%), likely *Atriplex* and *Chenopodium*, grew in dry settings in the basin and adjacent foothills. *Artemisia tridentata* was likely growing below lower tree line and within open forest of *Pinus flexilis* and *Pseudotsuga menziesii* at middle elevations, and open forest of *Pinus albicaulis*, *Picea engelmannii*, and *Abies lasiocarpa* was present at high elevations. *Juniperus* species at this time likely included *J. communis, J. horizontalis*, and *J. scopulorum,* with *J. scopulorum* growing at low elevations. Riparian areas likely supported *Salix* species, such as *S. boothii* and *S. bebbiana.*

DISCUSSION

The environmental history of the Rocky Mountain region is modeled by paleoclimate simulations for the western US at 21,000, 16,000, 14,000, 11,000, 6000, and 3000 cal yr BP and their comparison with paleoenvironmental data (Bartlein et al., 1998; Thompson et al., 1993). These models describe the large-scale changes in atmospheric circulation, and provide a context for interpreting local vegetation and climate changes at Lower Red Rock Lake. Other paleoecological records also provide information on vegetation and climate changes in the region, and were used for comparison to the Lower Red Rock Lake record. Grays Lake in southeastern Idaho has similar modern vegetation as Lower Red Rock Lake, and also provides a record that extends back to full-glacial conditions (Beiswenger, 1991). However, there is some concern about the Grays Lake chronology given the identification of the China Hat tephra, which dates at 61,000 ± 6000 yr BP (K-Ar) and lies stratigraphically between dates of 47,200 ± 120 and 45,500 ± 2160 ^{14}C yr BP in the Grays Lake record (Beiswenger, 1991). The late-glacial and Holocene record at Grays Lake, however, is constrained by 12 radiocarbon dates, and provides a good comparison for the inferred vegetation reconstruction at Lower Red Rock Lake. A record from Hedrick Pond (located in Grand Teton National Park) with radiocarbon ages as old as 20,000 cal yr BP also has similar vegetation to Lower Red Rock Lake and provides information from the full-glacial period (Whitlock, 1993).

Other records located at lower treeline in the northern Rocky Mountains span the late-glacial and Holocene periods and provide the opportunity to examine regional patterns in the climate and vegetation history. These sites from west to east are: McCall

Fen in west-central Idaho (Doerner and Carrara, 2001); Decker Lake near the Sawtooth Mountains of central Idaho (Whitlock, Unpublished data); and Pintler Lake in the Big Hole basin, southwest Montana (Brunelle et al., 2005) (Figure 5).

McCall Fen (44° 56’ N, 116° 02’ W; 1615 m elev.) is located in Long Valley, Idaho, and surrounded by sagebrush steppe in the valley. This vegetation is largely a result of outwash substrate on the valley floor that prevents forest development. Nearby forests are composed of pine, Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), grand fir (*Abies grandis*), subalpine fir (*Abies lasiocarpa*), and Engelmann spruce (*Picea engelmannii*). To the southeast of McCall lies Decker Lake (44° 4’ N, 114° 53’ W; 2167 m elev.), which is surrounded by lodgepole pine (*Pinus contorta*) forest with sagebrush steppe growing in the Stanley Basin (Whitlock, Unpublished data). Pintler Lake (45° 50’ N, 113° 26’ W; 1921 m elev.) is northeast of Decker Lake and northwest of Lower Red Rock Lake, within forests of lodgepole pine, and just above steppe vegetation in the Bighole Basin. Grays Lake (43° 5’ N, 111° 30’W, 1940 m elev.) lies southeast of Lower Red Rock Lake, in an active fault basin that supports sagebrush steppe with pine-juniper forests on nearby hills. Finally, Hedrick Pond (43° 45’ N, 110° 36’ W; 2073 m elev.) in Grand Teton National Park is surrounded by open mixed conifer forest, but adjacent to sagebrush steppe on glacial outwash gravel in Jackson Hole.

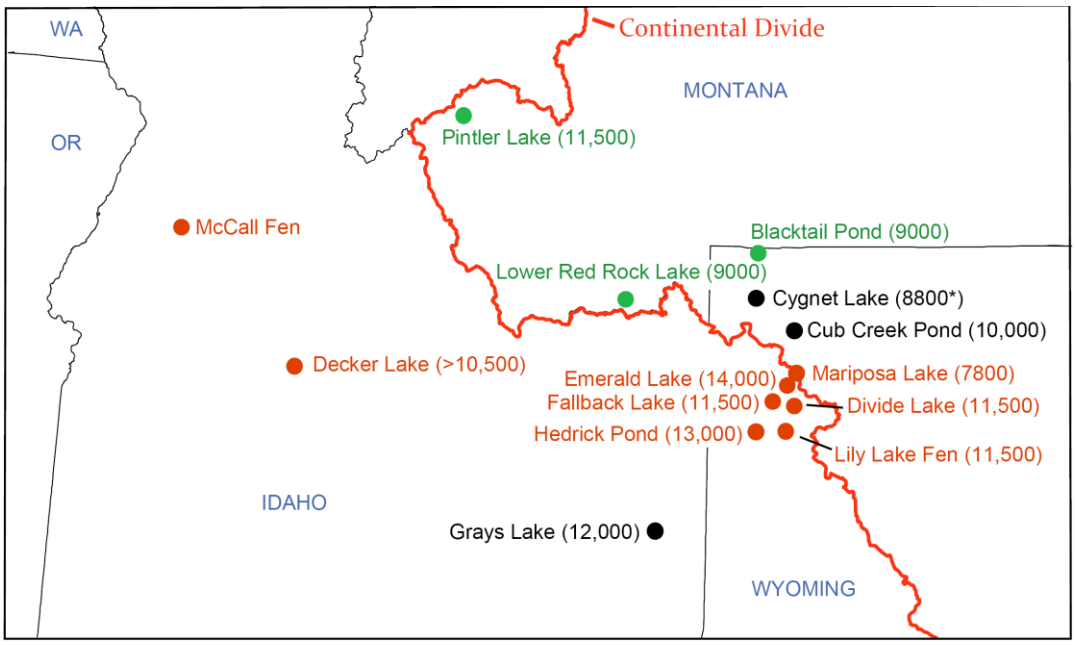


Figure 5. Location of Northern Rocky Mountain sites discussed in this paper. Sites in orange represent summer-dry sites, and sites in green represent summer-wet sites (discussed later). Sites in black are in transitional climate regimes. Numbers in parentheses are cal yr BP, and show approximate arrival of *Pseudotsuga* at each site. **Pseudotsuga* does not grow at Cygnet Lake today, but trace amounts of its pollen record its presence in the vicinity of the lake.

All of these sites are affected by moist Pacific storms tracking along the jet stream and up the Snake River Plain in the winter months, and under the influence of the northeastern Pacific subtropical high-pressure system which brings warm, dry air to the region in summer.

For comparison purposes, the pollen zone boundaries at Lower Red Rock Lake were used to define the full-glacial period (LRRL-05; >17,000 cal yr BP), late-glacial period (LRRL-04; 17,000 to 10,500 cal yr BP), and early Holocene (LRRL-03; 10,500-7100 cal yr BP), middle Holocene (LRRL-02; 7100-2400 cal yr BP), and late-Holocene intervals (LRRL-01; 2400 cal yr BP to present). Radiocarbon ages of the other records

were converted to cal yr BP where necessary using the online Calib program (http://intcal.qub.ac.uk/calib/; Stuiver et al., 2005).

Full-Glacial Period (> 17,000 Cal yr BP)

Prior to 17,000 cal yr BP, summer insolation was near its modern value and produced favorable conditions for the formation of large ice sheets in the northern US and Canada, and regional alpine glaciers within the Rocky Mountains (Pierce, 2004). Large-scale features of simulated paleoclimate for the full-glacial period include southerly displacement of the jet stream, which brought cold, dry continental air masses south of the Laurentide ice sheet (Bartlein et al., 1998; Locke, 1990). Models also suggest that a glacial anticyclone weakened westerly flow and prevented wet Pacific air masses from bringing moisture eastward.

Cosmogenic dating on 11 Pinedale age moraines in the Yellowstone region suggest that glacial recession occurred from 14,000 to about 17,000 ^{10}Be yr BP (Licciardi and Pierce, 2008). Pinedale end moraines near the base of the eastern Centennial Mountains indicate the presence of alpine glaciers near Lower Red Rock Lake during the full-glacial period, and large alluvial fans on the valley floor were likely enhanced by outwash from these alpine glaciers. Along the Elk Lake-Cliff Lake paleovalley lie landslides which were probably more active during the full-glacial period, and likely dammed passage of Red Rock River to the Madison River Valley to form Pleistocene Lake Centennial.

The lithology of LRRL 06P49 from Lower Red Rock Lake shows evidence of Pleistocene Lake Centennial formation in the abrupt change from Unit 3 to Unit 4, where fluvial sands abruptly shift to deep water lacustrine deposits. A conservative estimate based on chronology Option 2 places lake formation at roughly 20,000 cal yr BP, however, it may date back to ca. 28,000 cal yr BP (Option 1). High magnetic susceptibility values in LRRL 06P49 Unit 3 and Unit 4 indicate significant allochthonous sediment input at this time which was likely the result of 1) stream-transported sands early in the record (Unit 4), and 2) fine sediment deposition enhanced by active alpine glaciers after lake formation (Unit 3). Glacial flour and loess likely supplied a large amount of sediment to Pleistocene Lake Centennial, and vegetation was sparse at this time, contributing to sediment through erosion and solifluction near lake shores. Low organic content in LRRL 06P49 Unit 3 and Unit 4 confirms that the lake was not highly productive during this interval.

Pollen data indicate that the full-glacial vegetation around Lower Red Rock Lake was sparse and resembled modern alpine tundra with high amounts of Cyperaceae, Poaceae and herbaceous taxa. The dominant trees were likely *Picea engelmannii*, *Abies lasiocarpa* and *Pinus albicaulis*, which grow in modern high-elevation areas at present, and trees were probably sparsely distributed on low hills below the glaciated mountains. The percentage data, PAR and pollen concentrations are consistent with a full-glacial tundra landscape and indicate cold, dry conditions in the Centennial Valley.

Other pollen records that extend back this far also suggest cold, dry full-glacial conditions (Figure 6). Grays Lake in southeastern Idaho supported *Artemisia* steppe on the basin floor with conifers in the nearby foothills (Beiswenger, 1991). These conifers included *Picea* and *Abies*, which grow at high elevations at present. Hedrick Pond, GTNP also shows cold and dry conditions until about 18,000 cal yr BP, with high percentages of *Artemisia, Sarcobatus*, Poaceae, Asteraceae Tubuliflorae and little conifer pollen.

In the Pacific Northwest, Carp Lake (45° 55' N, 120° 53' W; 714 m elev.) is a volcanic crater lake on the slopes of the eastern Cascade Range. The lake is presently surrounded by *Pinus ponderosa* forest. The pollen record from Carp Lake extends to 125,000 cal yr BP, recording vegetation history into the last interglacial period (Whitlock and Bartlein, 1997). Although modern vegetation and climate in this area differs from the Rocky Mountain region, Carp Lake records similar conditions from 30,900 to 13,200 cal yr BP as the full-glacial conditions at LRRL, Grays Lake and Hedrick Pond. High percentages of *Artemisia*, Poaceae, and herbs with low percentages of *Picea* at this time suggest cold, dry steppe vegetation during the full-glacial period (Whitlock and Bartlein, 1997). This was likely the result of southerly displacement of the jet stream, which brought cold arctic air to the area and weakened westerly flow, which limited Pacific storms from bringing moisture into the area.

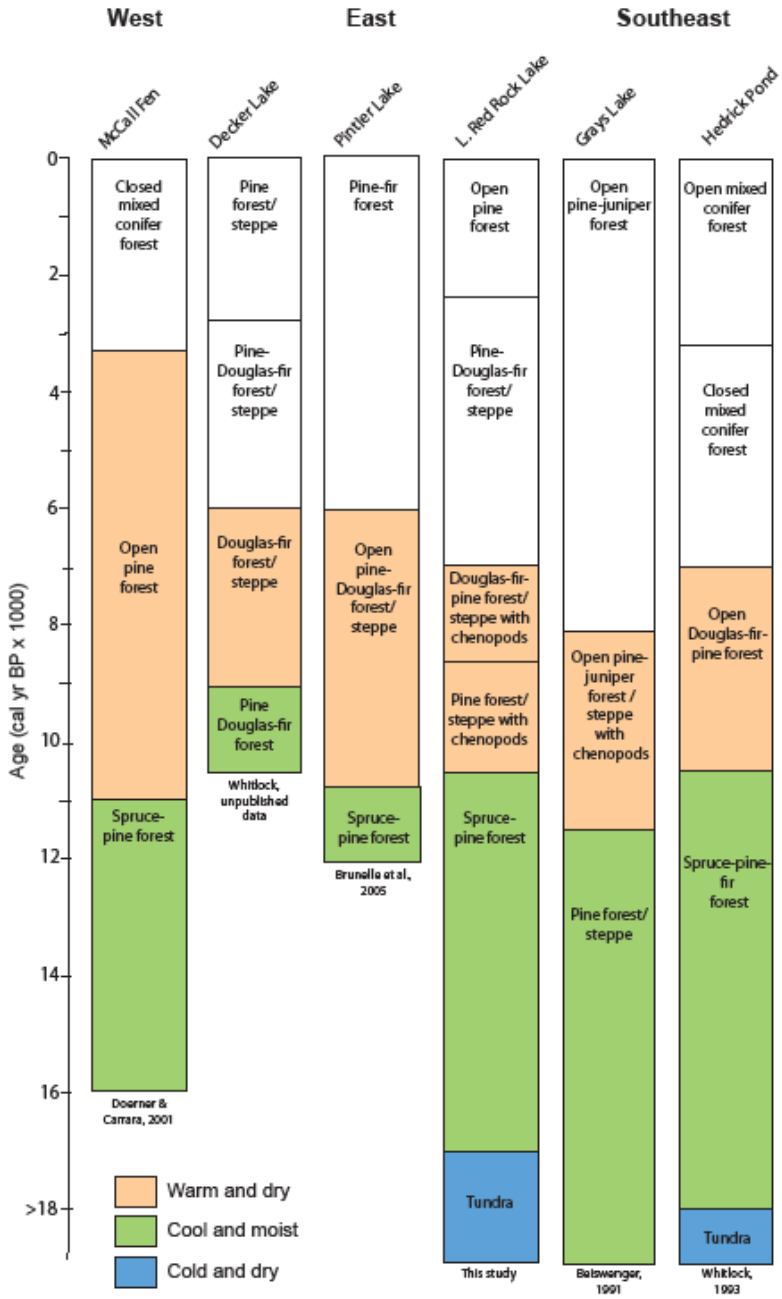


Figure 6. Summary of vegetation history from Northern Rocky Mountain pollen records.

Thus, the picture from the three full-glacial records confirms paleoclimate model inferences that the northwestern US, including the Rocky Mountain region, was cold and dry; and implies that treeline was significantly lower-than-present at all sites, perhaps as low as 500 m below present, as suggested for the Front Range of Colorado by Legg and Baker (1980).

Late-Glacial Period (17,000 to 10,500 Cal yr BP)

Increasing summer insolation during the late-glacial period had direct and indirect effects on western US climate at this time, based on paleoclimate model simulations for 16,000, 14,000, and the early-Holocene period (Bartlein et al., 1998; Thompson et al., 1993). First, increased summer insolation directly increased summer temperatures. Increased summer temperatures decreased effective moisture, but areas in close proximity to moisture from melting glaciers in the Rocky Mountain region might not have experienced this aridity initially. Second, increasing summer insolation indirectly strengthened the northeastern Pacific subtropical high-pressure system, which led to warm, dry summers in the late-glacial and early Holocene periods. Paleoclimate model simulations also suggest that a northward shift of the jet stream may have increased winter precipitation in this region (Bartlein et al., 1998).

At the start of the late-glacial period, Pleistocene Lake Centennial may have had depths of about 20 m. However, at the end of the late-glacial period, lake level was likely nearing its present depth (Pierce, Unpublished data). This period of time coincides well with LRRL 06P49 lithologic Unit 2 (17,000 to 11,000 cal yr BP), in which inorganic clay

gradually changed to marl with organic detritus and gastropod shells. Organic and carbonate content increased in this unit. Increasing organic content supports a gradual shift to a more productive lake, and the abundance of carbonates suggests that increasing water temperatures decreased solubility of bicarbonate (Burton and Walter, 1987) while warmer summers probably increased evaporation from the lake. The lithology of LRRL 06P49 Unit 2 implies a gradual transition from a large oligotrophic lake to a shallower, more productive system. Decreasing magnetic susceptibility in this unit suggests less allochthonous sediment input and better stabilized slopes.

Increases in PAR, pollen concentration, and arboreal pollen percentages imply more forest cover near Lower Red Rock Lake in late-glacial time. High pollen percentages for *Pinus, Picea* and *Abies* indicate that low elevation forests in the Centennial Mountains were likely composed of *Pinus albicaulis, Picea engelmannii, Abies lasiocarpa* and *Juniperus communis*. All of these conifers grow at high elevations in the Centennial Mountains today and are tolerant of very cold January temperatures (Thompson et al., 2000). Increased pollen percentages of *Salix, Alnus* and *Betula* suggest an increase in available moisture to support shrubs along riparian corridors. High percentages of Asteraceae Tubuliflorae and Poaceae pollen imply the presence of open meadows, indicating that the late-glacial landscape likely resembled subalpine parkland with open forests of *Pinus, Abies* and *Picea*.

The climate was colder than at present but warmer and effectively wetter than during the full-glacial period. This inference is based on the increase in forest cover, although the vegetation was more open than at present. Persistently higher percentages

of herbs than today and the absence of low-elevation conifers (e.g. *Pseudotsuga*) indicate cooler conditions than at present. Wetter conditions than during the full-glacial period are implied by increasing percentages of riparian taxa.

This period of warmer and wetter conditions after 17,000 cal yr BP coincides broadly with Pinedale deglaciation, although the timing precedes culmination of the Yellowstone ice field (Licciardi and Pierce, 2008). Seven cosmogenic ages from the Pine Creek moraine north of Yellowstone National Park places ice recession on the northern margin of the Pinedale age Yellowstone ice complex at ca. 17.6 ± 1400 ^{10}Be yr BP. This age also marks the vegetation shift towards thermophilous plant communities at Lower Red Rock Lake.

Other records also provide evidence of a cool, moist environment in the late-glacial period (See fig. 6). At McCall Fen in west central Idaho, cold, dry conditions persisted until about 14,000 cal yr BP, at which point conditions became warmer and wetter than the full-glacial period. The pollen data indicate development of a *Picea-Pinus* forest around the site (Doerner and Carrara, 2001). The pollen record from Pintler Lake shows cool, wet conditions before 11,000 cal yr BP, as suggested by the presence of *Picea* parkland and alpine environments. Grays Lake features high *Picea* percentages as well as increasing Cyperaceae, which also suggests cool, wet conditions. Finally, Hedrick Pond registers cool, wet conditions until about 11,500 cal yr BP, with increasing *Pinus*, *Abies* and *Picea* (Whitlock, 1993).

All sites at low elevations in the Northern Rocky Mountains experienced similar climatic conditions during the late-glacial period, as evidenced by increasing arboreal

pollen percentages, dominated by *Pinus*, *Picea*, and *Abies*. Although the modern ranges of the numerous Rocky Mountain *Pinus* species vary, *Picea* and *Abies* grow at high elevations at all sites today, implying cooler conditions than at present. Still, the presence of these arboreal taxa implies an overall warming from the full-glacial period, with an increase in available moisture.

The Younger Dryas Interval at Lower Red Rock Lake

The Younger Dryas event is a period of rapid cooling in the Northern Hemisphere following a period of general warming in the late-glacial period. It has been defined as the time period from about 12,900 to 11,600 cal yr BP in Greenland ice-core records (Alley, 2000), and many sites across western North America show climate fluctuations during this interval (e.g., Hendy et al., 2002; Grigg and Whitlock, 1998). In the Rocky Mountains, this interval is marked by minor glacial advances in the Colorado Front Range (Benedict, 1985), the Wind River Range (Gosse et al., 1995a,b) and the Canadian Rockies (Reasoner et al., 1994). Pollen data from Black Mountain Lake and Sky Pond in the Colorado Rockies near Denver suggest downslope displacement of alpine treeline by as much as 120 m (Reasoner and Jodry, 2000).

The Lower Red Rock Lake pollen record does not show obvious climate reversal during Younger Dryas time, although there are subtle changes in vegetation that may be associated with minor climatic cooling. The Lower Red Rock Lake pollen record shows *Picea* and *Abies* both averaging 3% during the late-glacial period. At about 12,200 cal yr BP, however, percentages of *Picea* and *Abies* increase to 5% and 4%, respectively, and remain at elevated values for about 500 years. Since both of these genera are tolerant of

very cold temperatures (Thompson et al., 2000) and grow at high-elevations today, increases in their abundance over a short period of time could suggest a minor rapid cooling event in the Centennial Valley. This event was followed by warming as suggested by decreasing *Picea* and *Abies*, and a rise in xerothermic plant taxa in the Lower Red Rock Lake record.

Early-Holocene Period (10,500 to 7100 Cal yr BP)

The early Holocene was characterized by greater-than-present Northern Hemisphere summer insolation and lower-than-present winter insolation, which produced warmer, effectively drier summers than present. Summer insolation was higher than present between 12,000 and 6000 cal yr BP, and reached a maximum between 11,000 and 9000 cal yr BP as a result orbital forcing (Berger, 1978). Paleoclimate model simulations for 11,000 cal yr BP suggest that the summer insolation maximum strengthened the Pacific subtropical high pressure system off northwestern North America, which in turn suppressed summer precipitation relative to present. In contrast, winter insolation was low in the northern hemisphere during the early-Holocene period. Amplification of the seasonal cycle of insolation led to greater seasonality relative to today, with warmer, drier summers and colder, wetter winters in the northwestern US (Bartlein et al., 1998).

In the eastern Centennial Valley, Lower Red Rock Lake may have shrunk to its present surface area and dropped to a water depth of about 3 m as a result of its stabilized western outlet. It has likely remained at these conditions for most of the Holocene (Pierce, Unpublished data). In LRRL 06P49 Unit 1, organic and carbonate content

increased in the early Holocene, and allochthonous sediment input was minimal as evidenced by low magnetic susceptibility values. Lithologic data from Unit 1 supports warmer-than-present conditions in the early Holocene with increasing lake productivity, increased precipitation of inorganic carbonates, and a stabilized landscape after 11,000 cal yr BP.

Pollen data from Lower Red Rock Lake also reflect a warm, dry environment. The increases in PAR and pollen concentration suggest that forests became more abundant, and the decline of *Picea* and *Abies* percentages imply that these genera shifted their ranges to higher elevations. High-elevation forests likely consisted of *Pinus albicaulis, Abies lasiocarpa, Picea engelmannii* and *Pinus contorta*. The first percentages of *Pseudotsuga*-type pollen suggest that *Pseudotsuga menziesii* appeared in the basin at about 9000 cal yr BP and populated low-elevation forests. *Juniperus* pollen was likely from a combination of *Juniperus communis, J. horizontalis,* and *J. scopulorum,* which are present in the modern vegetation. *J. scopulorum* is a low-elevation tree and large pollen producer that tolerates arid conditions (Thompson et al., 2000). It may have been abundant during the early Holocene. *J. communis* and *J. horizontalis* have low drought tolerance, and survive very low winter temperatures (Thompson et al., 2000). They were likely a component of the high-elevation forests. Low pollen percentages of *Alnus, Salix,* and *Betula* suggest that arid conditions also reduced riparian zones during the early Holocene. Below lower treeline, *Artemisia* steppe grew around Lower Red Rock Lake. Chenopodiaceae, likely *Atriplex* and *Chenopodium*, probably occurred on saline soils just above the modern lake margins.

Although its pollen is a minor component of the record, it is possible that *Quercus*, probably *Quercus gambelii*, was nearby at low elevations, as the warm dry climate likely produced favorable conditions (Thompson et al., 2000). *Quercus gambelii* currently grows in northern Utah and Colorado, but is not present in the Lower Red Rock Lake vicinity today. Although the Northern Rocky Mountains do not support local *Quercus gambelii* growth today, warmer temperatures and summer drought could have allowed the species to migrate further north during the early Holocene.

The inferred vegetation assemblage, with an abundance of low elevation forest components, high PAR and pollen concentrations, and high organic and carbonate content at Lower Red Rock Lake are consistent with very warm and dry conditions during the early Holocene. Data from LRRL 06P49 implies that the early Holocene period reflects the warmest, driest conditions of the Lower Red Rock Lake pollen record. The early-Holocene vegetation at other sites in the Northern Rocky Mountains also suggests an expansion of xerophytic vegetation, although the timing of inferred warmer and drier conditions is variable (See fig. 6). At McCall Fen, warm, dry conditions began around 11,000 cal yr BP and persisted about 3700 years longer than at Lower Red Rock Lake (Doerner and Cararra, 2001) as evidenced by a period of open pine forest. The long duration of the warm dry period at McCall Fen might be explained by a difference in elevation at that site, as McCall Fen is at least 300 m lower than the other sites. Decker Lake supported *Pseudotsuga* forest with steppe from about 9000 to 6000 cal yr BP and, unlike the present forest, *Pinus contorta* was a relatively minor component. The vegetation history from Pintler Lake near the Big Hole Basin also suggests a warm dry

period from 10,800 to 6000 cal yr BP when forests of *Pseudotsuga* and *Pinus* replaced the earlier communities of *Picea* and *Pinus*. Grays Lake in southern Idaho experienced warm dry conditions from 11,500 to 7900 cal yr BP, with an open *Pinus-Juniperus* forest and chenopod-steppe vegetation. The dominant *Juniperus* species at this time is believed to be *Juniperus osteosperma*, which grows in the Great Basin and lower slopes around the site (Beiswenger, 1991). At Hedrick Pond, warm dry conditions persisted from about 11,500 to 7000 cal yr BP as *Pinus*, *Picea* and *Abies* were replaced with high percentages of *Pseudotsuga*. Poaceae and Cyperaceae pollen also decreased at this time in the record, indicating a decrease in available moisture. Although the timing differs somewhat at each site, these pollen records imply that the early Holocene, from as early as 11,500 to as late as 3400 cal yr BP, was a time of greater-than-present warmth and aridity in the Northern Rocky Mountains. The records feature high pollen percentages of taxa that are tolerant of drought and high summer temperatures, and in general, these taxa replace higher-elevation taxa which were more prominent of the late-glacial record.

Middle-Holocene Period (7100 to 2400 Cal yr BP)

Paleoclimate model simulations for 6000 and 3000 cal yr BP show the influence of decreasing summer insolation and increasing winter insolation in the western US. These models suggest that decreasing summer insolation and weakening of the subtropical high-pressure system after 6000 cal yr BP led to cooler, effectively wetter summer conditions than before. Increasing winter insolation likely led to warmer, wetter winters than before (Bartlein et al., 1998).

During the middle-Holocene period, the landscape of the Centennial Valley remained very similar to that of the early Holocene. Lithology of Unit 1 is consistent with this interpretation, in that organic and carbonate content is similar to that of the early Holocene, and there was almost no clastic sediment input, as indicated by very low magnetic susceptibility values. The middle Holocene pollen record at Lower Red Rock Lake suggests increasing abundances of *Abies lasiocarpa*, Poaceae, and other herbs with continued presence of *Pseudotsuga menziesii*, low *Picea* percentages, and increased *Juniperus*. The continued presence of *Pseudotsuga menziesii* suggests that although cooler than the early Holocene, conditions were still warmer than those of the full and late-glacial periods. As before, drought-tolerant *J. scopulorum* was an important conifer at low elevations in the Centennial Mountains, and *J. communis* and *J. horizontalis* were present in upper-elevation forests. Increased Cyperaceae percentages indicate an expansion of wetlands around Lower Red Rock Lake, which today support *Carex* and *Eleocharis*.

At McCall Fen, open pine forest persisted until about 3100 cal yr BP, suggesting continued warm, dry conditions. The Decker Lake record shows development of more closed forest from 6000 to about 2800 cal yr BP, as *Picea* and *Abies* increased and *Pseudotsuga* declined. Likewise, the transition at 6000 cal yr BP from *Pseudotsuga menziesii* and *Pinus* forest to *Pinus-Abies* forest at Pintler Lake implies an increase in effective moisture. At Grays Lake, increases in *Pinus* and *Juniperus* pollen from ca. 7900 to 2000 cal yr BP indicate a shift towards cooler wetter conditions. At Hedrick Pond, percentages of Cyperaceae, *Picea* and Asteraceae Tubuliflorae at 7000 cal yr BP

suggest a shift from xerophytic to mesophytic taxa. These records are consistent with a shift to cool, moist conditions relative to the early Holocene in the Northern Rocky Mountains. Xerothermic vegetation persisted at low-elevation McCall Fen until ca. 3400 cal yr BP.

Late-Holocene Period (2400 Cal yr BP to Present)

Between 2400 cal yr BP and present day, summer and winter insolation in the northern hemisphere reached present values. Paleoclimate models show that there was more effective moisture in both winter and summer than during the early and mid-Holocene (Bartlein et al., 1998). At Lower Red Rock Lake, open forest of *Pinus flexilis*, *Pseudotsuga menziesii*, and *Juniperus scopulorum* developed at low elevations, and closed forests of *Picea engelmannii*, *Pinus albicaulis*, and *Abies lasiocarpa* grew at high elevations. Decreases in *Artemisia* percentages suggest that forests became more closed, possibly out-competing shade-intolerant *Artemisia*. The Increases in Poaceae and Cyperaceae pollen mark the expansion of wetlands beyond the lake margin.

From 2400 cal yr BP to present at McCall Fen, cool and moist conditions supported the development of *Pinus ponderosa*, *Pinus contorta*, *Picea engelmannii*, *Pseudotsuga menziesii*, *Larix occidentalis* and *Abies grandis* forests. Vegetation at Decker Lake transitioned from open *Pinus-Pseudotsuga* forest to closed *Pinus contorta* forest with steppe at lower elevation after about 2800 cal yr BP. Pintler Lake continued to support *Pinus-Abies* forest, and the pollen record there shows an overall increase in arboreal pollen after 3000 cal yr BP, suggesting an increase in forest cover. This also

implies increasing moisture, as does the Grays Lake record, which shows an increase in Cyperaceae pollen after about 2000 cal yr BP. Hedrick Pond shows abundant *Picea*, *Abies* and *Salix* from 1600 cal yr BP to present. These records indicate cool conditions during the late Holocene, although average summer temperatures were higher than those of the full and late-glacial periods, yet lower than those of the early Holocene. All sites also suggest an increase in available moisture from the early and middle Holocene to the late Holocene, as reflected in the expansion of wetland taxa and high-elevation trees.

History of *Pseudotsuga menziesii* at Northern Rocky Mountain Sites

The pollen record from Lower Red Rock Lake suggests that *Pseudotsuga menziesii* appeared in the Centennial Valley during the early Holocene at about 9000 cal yr BP. However, the timing of this arrival is not consistent with other sites in the Northern Rocky Mountains (See fig. 5). The Decker Lake pollen record suggests that *Pseudotsuga* was present by 10,500 cal yr BP, however the record does not extend farther back in time and it is possible that *Pseudotsuga* migrated to the Sawtooth Range even earlier. *Pseudotsuga*-type pollen is first present in the Pintler Lake record at about 11,500 cal yr BP. It should be noted, however, that *Larix occidentalis* also grows near Pintler Lake today, and pollen in the record might not be exclusively from *Pseudotsuga*. Grays Lake shows *Pseudotsuga*-type pollen in significant percentages at ca. 12,000 cal yr BP, although the chronology provides poor temporal resolution (Beiswenger, 1991), and Hedrick Pond features minor *Pseudotsuga*-type percentages as early as 13,000 cal yr BP.

The McCall Fen record does not include *Pseudotsuga*-type pollen, even though *Pseudotsuga menziesii* grows there today.

Tsukada (1982) suggests that northern full-glacial refugia of *Pseudotsuga* were found in northern Idaho and Montana (on the Pacific side of the Continental Divide) during the full-glacial period, and that this Rocky Mountain variety of *Pseudotsuga menziesii* (var. *glauca*) migrated westward into Washington during the early-Holocene period. Full-glacial age *Pseudotsuga menziesii* macrofossils were also found in packrat middens from southern Utah (Betancourt, 1990), and sediments from the Great Salt Lake record *Pseudotsuga* presence there in the late Pleistocene (Mehringer, 1977). These occurrences indicate that *Pseudotsuga* also grew south of Lower Red Rock Lake during the full-glacial period.

The relatively late appearance (ca. 9000 cal yr BP) of *Pseudotsuga* at Lower Red Rock Lake relative to other sites may be explained by geographic variations in early-Holocene climate. In addition, the steep topographic gradients of the northern Rocky Mountains may have hindered *Pseudotsuga*'s ability to move from full-glacial refugia into the Centennial Valley, even though the climate may have been suitable for it prior to 9000 cal yr BP. The Continental Divide trends east-west across the Centennial Mountains, and Lower Red Rock Lake is located north of the divide in the Atlantic drainage. Other sites north of the Continental Divide show similar late timing for the arrival of *Pseudotsuga menziesii*. At Blacktail Pond in northern Yellowstone National Park (YNP), *Pseudotsuga menziesii* arrives at about 9000 cal yr BP (Huerta et al., 2009). Mariposa Lake, which lies on the Two Ocean Plateau of southern YNP, also registers

Pseudotsuga at about 7800 cal yr BP (Whitlock, 1993), and although *Pseudotsuga* did not grow near Cygnet Lake due to inhospitable rhyolitic substrate (Whitlock, 1993), trace amounts of its pollen suggest its arrival in central YNP at about 8800 cal yr BP. Cub Creek Pond registers *Pseudotsuga* arrival at ca. 10,000 cal yr BP (Waddington and Wright, 1974). Sites south and west of the Continental Divide (on the Pacific side) including Decker Lake, Pinter Lake, Grays Lake, and Hedrick Pond, all show significantly earlier arrival of *Pseudotsuga* (>10,500, 11,000, and 13,000 cal yr BP, respectively) than at Lower Red Rock Lake. In addition to these sites, lakes south of the Continental Divide in Yellowstone and Grand Teton National Parks also show early arrival of *Pseudotsuga*. These include Fallback Lake (arrival ca. 11,500 cal yr BP), Lily Lake Fen (arrival ca. 11,500 cal yr BP), Divide Lake (arrival ca. 11,500 cal yr BP), and Emerald Lake (arrival ca. 14,000 cal yr BP) (Whitlock, 1993).

The difference in arrival times of *Pseudotsuga* at sites on the Pacific and Atlantic sides of the Continental Divide in the late Pleistocene and early Holocene suggests that this topographical feature was somehow a barrier to *Pseudotsuga* establishment on the Atlantic side of the Continental Divide. This could possibly be a result of (1) the high elevations of the Continental Divide, which would have served as a climatic barrier to the migration of *Pseudotsuga menziesii* as it established itself in the Northern Rocky Mountains on the Pacific side of the continent and/or (2) spatially variable environmental conditions at lower elevations on the Atlantic side of the Continental Divide, which were not favorable for *Pseudotsuga* establishment in the late-glacial and early-Holocene periods.

The generally high elevations of the mountain ranges that comprise the Continental Divide might have effectively blocked the seed transport and seedling establishment from refugia that existed on the Pacific side of the Continental Divide. *Pseudotsuga* pollen is not transported long distances (Tsukada, 1982; Silen, 1962). *Pseudotsuga menziesii* grows predominantly at low elevations and cannot tolerate winter temperatures lower than about -10°C (Thompson et al., 2000). During the cool, moist late-glacial period, high elevations were still covered by glaciers and probably too cold for *Pseudotsuga menziesii* growth. Therefore, mountain barriers could have temporarily delayed *Pseudotsuga menziesii* from expanding its range from low elevations on the Pacific side of the Continental Divide to suitable areas on the Atlantic side.

Whitlock and Bartlein (1993) discuss topographically-driven spatial variations of climate in the Northern Rocky Mountains and their influence on regional climate histories. Today, the western US exhibits two climate regimes: summer-wet and summer-dry. These regimes are based on the ratio of modern July precipitation to January precipitation. The summer-wet precipitation regions are areas where monsoonal circulation from the Gulf of California and Gulf of Mexico brings significant summer precipitation. This pattern typifies the climate of the southwestern US and extends to the southern Rocky Mountains and Great Plains. The summer-dry precipitation regime refers to regions where summer precipitation is suppressed as a result of the influence of the northeastern Pacific subtropical high-pressure system and is best expressed in the Pacific Northwest. Both of these precipitation regimes are found in the Northern Rocky Mountains, and topography plays a large role in their relative influence. Variations in

topography control storm tracks in this region and determine how these two climate regimes manifest themselves at individual sites. Therefore, although two sites may be relatively close to one another spatially, they may experience contrasting precipitation regimes.

In the early-Holocene period, Whitlock and Bartlein (1993) suggest the intensification of these precipitation regimes in response to increased summer insolation. Greater-than-present summer insolation intensified the northeastern Pacific subtropical high-pressure system and increased monsoonal circulation (Bartlein et al., 1998). The early Holocene was characterized by drier-than-present summers in summer-dry regions and wetter-than-present summers in summer-wet regions. The Rocky Mountain variety of *Pseudotsuga menziesii (*var. *glauca)* grows well in semi-arid environments at present and is much more tolerant of drought than its Pacific Northwest relative, *Pseudotsuga menziesii* var. *menziesii* (Tsukada, 1982). *P. menziesii* var. *glauca* currently grows in continental climates with hot, dry summers and dominantly winter precipitation in the form of snow (Hermann and Lavender, 1990). As a result, contrasting cool wet summers in the early Holocene may have prevented the establishment of *Pseudotsuga* at sites in the summer-wet regions and warm dry conditions in summer-dry regions would have promoted its expansion. These climate differences would explain the arrival of *Pseudotsuga* at summer-dry sites (Emerald Lake, Fallback Lake, Hedrick Pond, Mariposa Lake, Divide Lake, Lily Lake fen, Decker Lake) before its arrival at summer-wet sites (Blacktail Pond, Lower Red Rock Lake, Pintler Lake) (See fig. 5). An exception to the pattern is Mariposa Lake, a summer-dry site, where *Pseudotsuga*'s arrival occurred fairly

late, at 7800 cal yr BP. The site is located at a higher elevation (2730 m elev.) than other summer-dry sites, and elevational temperature gradients may have limited *Pseudotsuga* arrival at Mariposa Lake in the early Holocene. Thus, geographic differences in summer precipitation and temperature in the early Holocene may have promoted an early arrival of *Pseudotsuga* in summer-dry regions and delayed its establishment in summer-wet regions until conditions became warmer and drier in the middle-Holocene period.

CONCLUSIONS

The environmental history of the eastern Centennial Valley is inferred from the record at Lower Red Rock Lake and its comparison of other paleovegetation and paleoclimate records in the Northern Rocky Mountains, and our understanding of regional climate based on paleoclimate model simulations. Specifically, the following conclusions have been drawn from this study:

1) The vegetation at Lower Red Rock Lake prior to 17,000 cal yr BP resembled modern alpine tundra with high percentages of grasses and herbs, suggesting cold and dry conditions in the Centennial Valley. High-elevation trees shifted their present ranges downslope and grew at lower elevations than today in an open landscape. The abrupt transition from sand to deep-water clays in core LRRL 06P49 provides evidence of the rapid formation of Pleistocene Lake Centennial with water depths of about 20 m at or prior to ca. 20,000 cal yr BP. Between 17,000 and 10,500 cal yr BP, conditions were warmer and effectively wetter than before. Development of subalpine parkland coincides with regional deglaciation associated with the Yellowstone glacier complex (Licciardi and Pierce, 2008). During this time, lake level lowered as its western outlet deepened and became stable. Between 10,500 and 7100 cal yr BP, higher-than-present summer insolation brought warmer, drier conditions to the Centennial Valley, which is reflected by low values of *Picea*, *Abies*, *Juniperus*, Poaceae, Cyperaceae, and increasing percentages of Chenopodiaceae; and the first appearance of *Pseudotsuga* at 9000 cal yr BP. Lake levels were near their present depth at this time, and productivity increased at Lower Red Rock Lake. Middle-Holocene conditions (ca. 7100 to 2400 cal yr BP) were

wetter and cooler than the early Holocene and throughout the region, mesophytic taxa replaced drought-adapted plants and wetlands expanded. More abundant high-elevation trees after 2400 cal yr BP indicate conditions that were cooler and wetter than before. The present climate and vegetation at Lower Red Rock Lake reflect the coolest and effectively wettest climate in the last 10,000 years.

2) The inferred climate history from the Lower Red Rock Lake pollen record corresponds well with paleoclimate models and with climate reconstructions from other late Pleistocene records in the northern Rocky Mountains. Full-glacial cold and dry conditions (>17,000 cal yr BP) are explained by cold dry air masses associated with a southward shift of the jet stream. The late-glacial (17,000 to 10,500 cal yr BP) expansion of subalpine species is registered at all sites and consistent with warmer conditions than before and increased effective moisture. Paleoclimate model simulations suggest that the northward shift of the jet stream may have increased winter precipitation in this region. Increased summer drought in the early Holocene (10,500 to 7100 cal yr BP) is evidenced by the upslope shift in lower treeline at all sites and the records are consistent with high summer insolation and an expanded subtropical high pressure system at this time. Decreased summer insolation in the middle (7100 to 2400 cal yr BP) and late Holocene (2400 cal yr BP to present) led to cooler summers and warmer, wetter winters which provided favorable conditions for high-elevation forest components.

3) *Pseudotsuga* appears in the Lower Red Rock Lake pollen record at about 9000 cal yr BP, suggesting the arrival of *Pseudotsuga menziesii* (Douglas-fir) from glacial refugia. Late arrival (from 7800 to 11,000 cal yr BP) of *Pseudotsuga menziesii* also occurs at nearby sites on the Atlantic side of the Continental Divide. In pollen records from sites on the Pacific side, however, *Pseudotsuga menziesii* arrives much earlier (from >10,500 to 14,000 cal yr BP). Relative timing at these various sites suggests that the Continental Divide served as some sort of barrier to the north and eastward migration of *Pseudotsuga menziesii* in the northern Rocky Mountain region, possibly as a high-elevation climatic barrier to *Pseudotsuga menziesii* migration, or as a result of topographically-driven spatially variable climatic regimes which were intensified during the late-glacial and early Holocene periods.

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