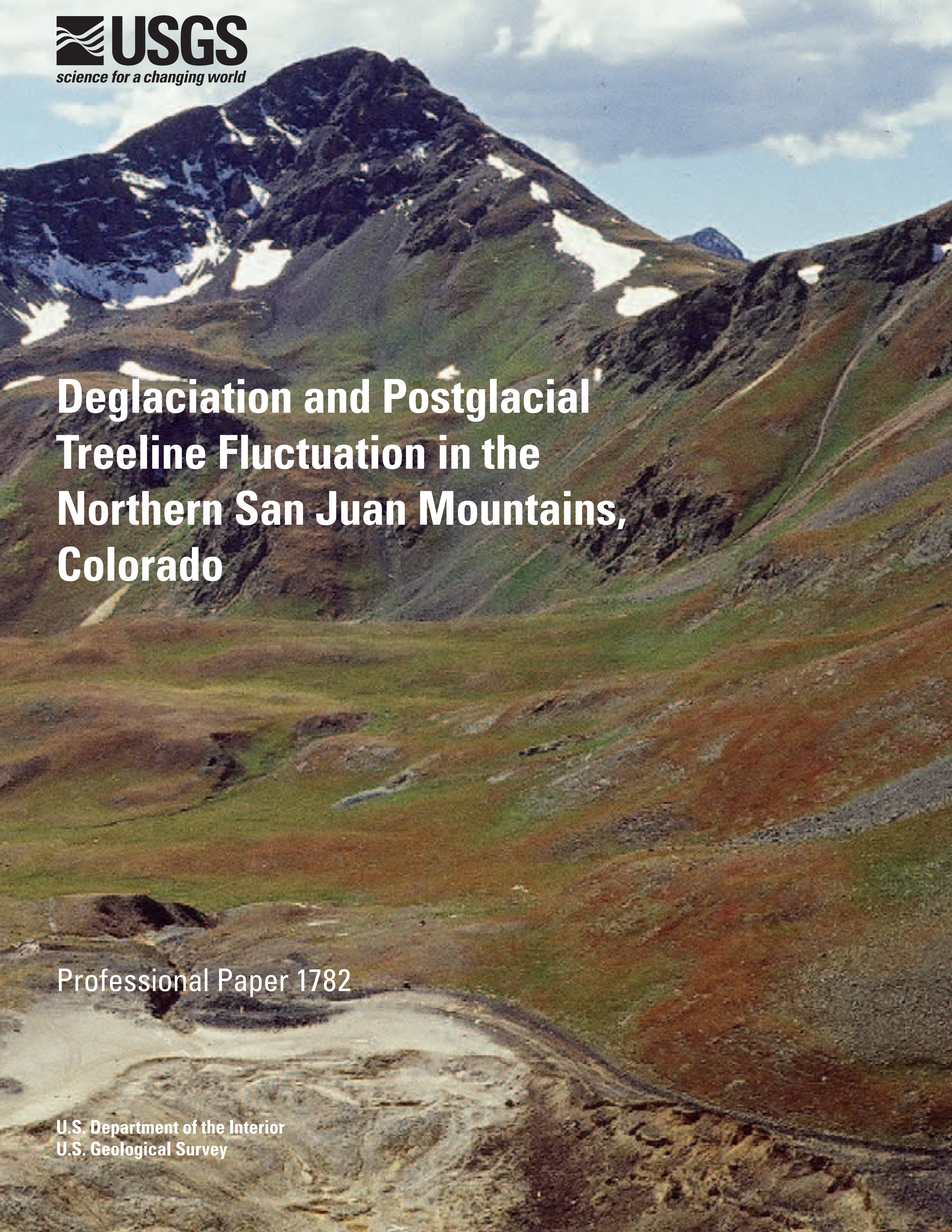

Deglaciation and Postglacial Treeline Fluctuation in the Northern San Juan Mountains, Colorado

Professional Paper 1782

U.S. Department of the Interior
U.S. Geological Survey

Cover photo: Site of former Lake Emma (foreground) and Emery Peak (4,057 meters) to the south, northern San Juan Mountains, Colo.

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By Paul E. Carrara

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Abbreviations Used in This Report

°C/km	degrees Celsius per kilometer
δD	delta deuterium (change in deuterium concentration)
<	less than
>	greater than
AMS	accelerator mass spectrometry
asl	above sea level
Be	beryllium
cal yr	calibrated radiocarbon age given in calendar years before present (present set to 1950 A.D.)
cm	centimeter, centimeters
cm/km	centimeter per kilometer
cm/yr	centimeter per year
ka	kiloannum (thousand years ago)
kg	kilogram, kilograms
km	kilometer, kilometers
km^2	square kilometer, square kilometers
m	meter, meters
m/yr	meter per year
per mil/°C	per mil per degree centigrade
U.S.	United States
yr B.P.	radiocarbon year before present (present set to 1950 A.D.)

Radiocarbon Laboratory Abbreviations Used in This Report

A	Laboratory of Isotope Geochemistry, University of Arizona, Tucson
AA	National Science Foundation–Arizona AMS Facility, University of Arizona, Tucson
CAMS	Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, Livermore, Calif.
CURL	Colorado University Radiocarbon Laboratory, Boulder, Colo.
DIC	Dicarb Radioisotope Laboratory, Chagrin Falls, Ohio*
GaK	Gakushuin University, Tokyo, Japan*
GX	Geochron Laboratories, Cambridge, Mass.
I	Teledyne Isotopes, Westwood, N.J.*
SI	Radiation Biology Laboratory, Smithsonian Institution, Rockville, Md.*
St	Laboratory of Isotope Geology, Swedish Museum of Natural History, Stockholm, Sweden*
USGS	U.S. Geological Survey, Menlo Park, Calif.*
W	U.S. Geological Survey, Reston, Va. (conventional radiocarbon age)*
WW	U.S. Geological Survey, Reston, Va. (accelerator mass spectrometry
Y	Yale University Radiocarbon Laboratory, New Haven, Conn.*

[*no longer operating]

Definitions Used in This Report

Radiocarbon ages	Reported in radiocarbon years before present (yr B.P.); “present” set to 1950 A.D.
Calendar years	Taken from Fairbanks and others, 2005 (cal yr); "present" set to 1950 A.D.
Cosmogenic ages	Labeled as ^{10}Be or ^{36}Cl ka; set from the year the ages were determined

Deglaciation and Postglacial Treeline Fluctuation in the Northern San Juan Mountains, Colorado

By Paul E. Carrara

Abstract

The San Juan Mountains of southwestern Colorado contain numerous lakes and bogs at and above treeline. In June 1978, Lake Emma, a tarn above present-day treeline, was suddenly drained by the collapse of underground mine workings. This study was initiated because the draining exposed a well-preserved archive of subfossil coniferous wood fragments that provided a unique opportunity to further our understanding of the paleoclimatic history of this region.

These paleoclimatic studies—coniferous macrofossil identification in conjunction with radiocarbon dating, deuterium analysis of the dated conifer fragments, as well as pollen and fossil insect analyses—yielded new information regarding Holocene climate and accompanying treeline changes in the northern San Juan Mountains. This report synthesizes previously published reports by the author and other investigators, and unpublished information of the author bearing on late Pleistocene and Holocene treeline and climate in this region.

Retreat of the glacier that occupied the upper Animas River valley from its Pinedale terminal position began about 19.4±1.5 ^{10}Be thousands of years ago and was essentially complete by about 12.3±1.0 ^{10}Be thousands of years ago. Two sets of late Pleistocene cirque moraines were identified in the northern San Juan Mountains. The older set is widespread and probably correlates with the Younger Dryas (11,000–10,000 radiocarbon years before present; 12,800–11,500 calendar years). The younger set is found only in the Grenadier Range and represents remnant glacier ice lying in well-shaded niches in a mountain range undergoing rapid deglaciation. A snowbank at the northern base of this range appears to be fronted by a Little Ice Age moraine.

Soon after deglaciation the average July temperature is estimated to have been about 5°C cooler and timberline about 650 meters lower than at present. However, timberline (and treeline) responded rapidly to the postglacial warming and reached higher-than-present elevations by the early Holocene.

A comparison of recently obtained accelerator mass spectrometry radiocarbon ages of coniferous wood fragments from Lake Emma, previously dated by conventional radiocarbon methods during the 1980s, led to a slight modification of previously published ages of Holocene treeline fluctuations. As early as 9,200 radiocarbon years before present (about 10,400 calendar years) and probably to about 5,400 radiocarbon years before present (about 6,200 calendar years), treeline was at least 80 meters higher than at present (about 3,660 meters). Furthermore, a large conifer fragment with a complacent annual ring record suggests that timberline may have been at least 140 meters higher than present (about 3,600 meters) about 8,000 radiocarbon years before present (about 8,900 calendar years). These past elevations of treeline and timberline suggest that growing-season temperatures were at least 0.5–0.9°C warmer than at present. Deuterium data from the Lake Emma wood samples suggests that the maximum average temperature change from about 9,000 to 5,400 radiocarbon years before present (about 10,150 to 6,200 calendar years) was about 4°C. Owing to these warmer temperatures the summer monsoon circulation, which currently brings a large part of the annual precipitation to the San Juan Mountains, probably was more intense during the early and middle Holocene than it is today.

Between about 5,400 and 3,500 radiocarbon years before present (about 6,200 and 3,770 calendar years) it appears that treeline was near its present-day limit. After 3,500 radiocarbon years before present (about 3,770 calendar years), evidence of treeline position is very sparse, suggesting that treeline lay at, or below, its present-day elevation. However, a spruce krummholz fragment from the Lake Emma site provided two radiocarbon ages of about 3,100 radiocarbon years before present (about 3,300 calendar years). It is not clear whether this wood fragment represents a short-lived climatic amelioration or whether it was from a unique individual that grew above the general treeline at that time.

Approximately 20 other studies at sites throughout western North America that have yielded records of conifer remains above present-day limits are presented in the appendix of this report. The results of many of these studies are similar to those obtained in this study and indicate a higher than present-day treeline during the early to middle Holocene.

Because this study is based on more than 100 radiocarbon ages, including 66 ages from 53 coniferous wood fragments from the Lake Emma site, as well as pollen and insect analysis and deuterium data from the wood fragments, this study represents one of the best-documented records of Holocene treeline fluctuations in North America.

Introduction

Background and Purpose

The study area lies in the northern San Juan Mountains of southwestern Colorado (fig. 1). This mountain range contains numerous lakes and bogs, many of which are at and above treeline. Investigations of the sediment and organic material recovered in these bogs, including pollen and conifer macrofossils, in conjunction with radiocarbon dating, produced considerable new information regarding upper treeline position during the early to middle Holocene. In addition, on 4 June 1978, Lake Emma (fig. 1), a tarn above present-day treeline, was suddenly and completely drained by the collapse of underground mine workings (Carrara and Mode, 1979; Marcus and Marcus, 1983; Carrara and others, 1984, 1991). The draining of Lake Emma provided a unique opportunity for paleoclimatic studies because the lake's sediments were incised by the escaping waters, which exposed a well-preserved archive of subfossil coniferous wood fragments above present-day treeline. Fifty-three of these coniferous fragments were subsequently radiocarbon dated (some several times) (Carrara and others, 1984, 1991), yielding one of the best-documented records of Holocene treeline fluctuations in North America. Because of concerns about anthropomorphic causes of global warming, the study and documentation of the natural variability in ecosystems is important in order to understand the possible effects of future climate change.

The elevation of upper timberline (the upper elevational limit of large, upright trees) and treeline (the upper elevational limit of krummholz—the stunted, scattered, and commonly prostrate trees that grow in physically stressed sites above timberline) is controlled by temperature during the growing season (Fritts, 1976; Tranquilli, 1979). The dating of krummholz coniferous wood fragments indicated periods of warmer than present-day summer temperatures. In addition, Friedman and others (1988) and Epstein and others (1999) measured deuterium concentrations in the cellulose of many of these krummholz fragments, which they interpreted as indicating warmer summer temperatures or increased precipitation from southerly sources (or both). Together, these studies yielded

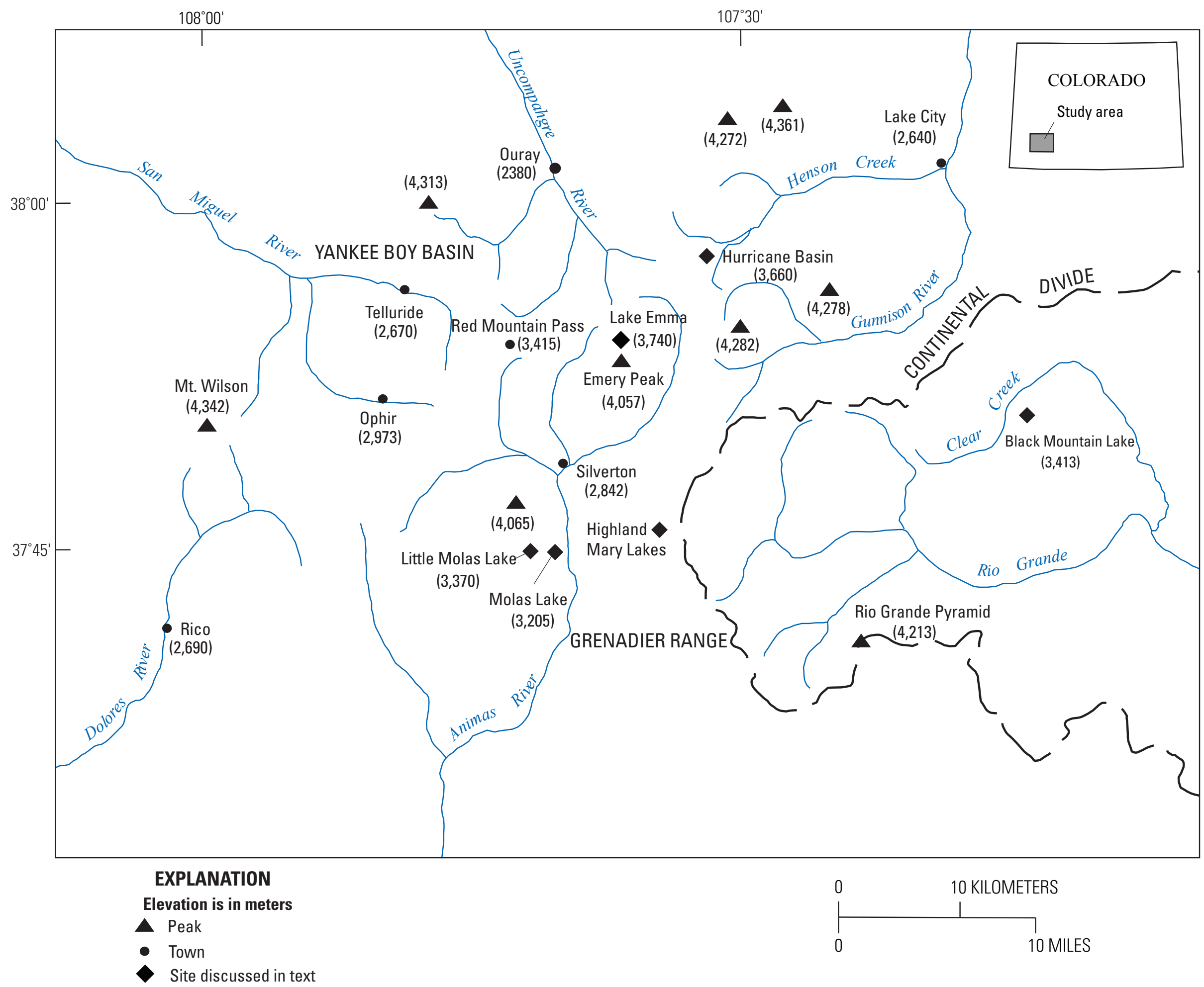


Figure 1. Northern San Juan Mountains and selected sites discussed in this study. Elevations in meters.

much information about Holocene treeline and climatic fluctuations in the San Juan Mountains.

The purpose of this report is to synthesize previously published reports by the author and by other investigators, and previously unpublished information bearing on late Pleistocene and Holocene treeline and climate in order to further our understanding of the paleoclimatic history of the northern San Juan Mountains of Colorado. The previously unpublished information consists of radiocarbon ages of coniferous wood fragments or other material associated with conifer remains from a water well drilled near the town of Telluride (fig. 1) in 1991 and from exposed sediments of Lake Emma collected between 1978 and 1987. These climate-related data from sites in the northern San Juan Mountains are presented and their implications for postglacial vegetation, Holocene treeline, and climate are then discussed.

Geography and Geology

The San Juan Mountains, situated along the Continental Divide, constitute a rugged mountainous region of about 20,000 square kilometers (km^2). About 2,000 km^2 lies in the alpine zone above timberline, and many peaks exceed 4,200 meters (m) in elevation. The mountain range contains the headwaters of the various tributaries of the Colorado River, including the Animas, Gunnison, San Miguel, and Uncompahgre Rivers, as well as the headwaters of the Rio Grande (fig. 1).

The San Juan Mountains consist of a sequence of middle to late Tertiary lava rocks and pyroclastic rocks as much as 2 kilometers (km) thick that were erupted from at least 15 calderas (Steven and Lipman, 1976). These volcanic rocks unconformably overlie metamorphosed sedimentary and volcanic rocks and intrusive rocks of Precambrian age, as well as sedimentary rocks of Paleozoic, Mesozoic, and early Cenozoic age (Steven and others, 1974; Casadevall and Ohmoto, 1977).

Vegetation Zones in the San Juan Mountains

Because of their elevation and relief, the San Juan Mountains contain a number of vegetation zones, as discussed in Maher (1961). Below about 2,285 m are what Maher (1961) describes as the “transition and Upper Sonoran zones.” In these zones, pinyon pine (*Pinus edulis*) and various species of juniper (*Juniperus scopulorum, J. monosperma,* and *J. osteosperma*) are abundant, as is scrub oak (chiefly *Quercus gambelii*). Ponderosa pine (*Pinus ponderosa*) is common down to about 1,825 m, and Douglas fir (*Pseudotsuga menziesii*) is restricted to north-facing slopes (Maher, 1961).

In the montane zone, between about 2,285 and 2,900 m, Douglas fir, scrub oak, and aspen (*Populus tremuloides*) are abundant (Maher, 1961). Blue spruce (*Picea pungens*) and white fir (*Abies concolor*) are also abundant above about 2,400 m. Dense stands of ponderosa pine can be found up to about 2,600 m, whereas Engelmann spruce *(Picea engelmannii)* and subalpine fir *(Abies lasiocarpa)* grow above this elevation (Maher, 1961). Limber pine (*Pinus flexilis*) is a minor component of the vegetation in this zone (Maher, 1961).

The subalpine forest zone, extending from about 2,900 m to timberline, is dominated by Engelmann spruce and subalpine fir (Maher, 1961). Above timberline, krummholz are dominated by Engelmann spruce and minor amounts of subalpine fir that reach to treeline. In the San Juan Mountains, timberline generally lies between 3,535 and 3,600 m, whereas treeline generally lies at about 3,660 m. Although bristlecone pine *(Pinus aristata)* and limber pine, two species commonly found at treeline in many areas in Colorado, have been reported in the San Juan Mountains (Maher, 1961; Arno and Hammerly, 1984), none were noted in the study area.

In the alpine zone, above about 3,660 m, vegetation consists mainly of herbs, such as sagebrush (*Artemisia* spp.), sedges (Cyperaceae), and grasses (Poaceae) that can survive the short growing season. Occasional patches of dwarf willow (*Salix* spp.) can be found up to an elevation of about 4,000 m.

The Timberline-Treeline Ecotone and Controlling Factors

The upper limits of alpine tree growth in the Northern Hemisphere generally correlate with the 10°C isotherm of the warmest month, usually July (Arno and Hammerly, 1984). This correlation is only approximate, because trees in most upper timberlines gradually become smaller and more deformed upslope. Thus, the positions of timberline and treeline are not precise (Arno and Hammerly, 1984, p. 13), and estimates of their positions can be subjective. In this study timberline was estimated as the upper altitudinal limit of upright trees generally taller than about 5 m.

Treeline was estimated as the upper altitudinal limit of krummholz, although in rare cases an individual grew above this limit. An example of a unique individual that grew above the general treeline limit is a dead krummholz found on a ridge above California Gulch (fig. 2). Although the tree had grown at an elevation of 3,870 m, about 200 m above the general treeline, it had grown in a sheltered niche at the base of a small south-facing cliff, where it received a sizeable amount of solar radiation. Wood collected from this individual yielded a radiocarbon age of 280±80 years before present (yr B.P.) (laboratory number W–6237; age is outside calibration range).

In addition to temperature, other factors such as aspect, cold-air drainage, snow, wind, and snow avalanches can influence local timberline and treeline. In the northern hemisphere they are generally higher on west- and south-facing slopes because these slopes receive more insolation.

Owing to cold-air drainage, many cirque and valley floors in the northern San Juan Mountains are devoid of conifers, whereas surrounding slopes or ridges may support patches of krummholz. Cold air commonly settles along valley floors such that frost may occur on most nights, while nearby slopes and ridges remain frost free (Arno and Hammerly, 1984).

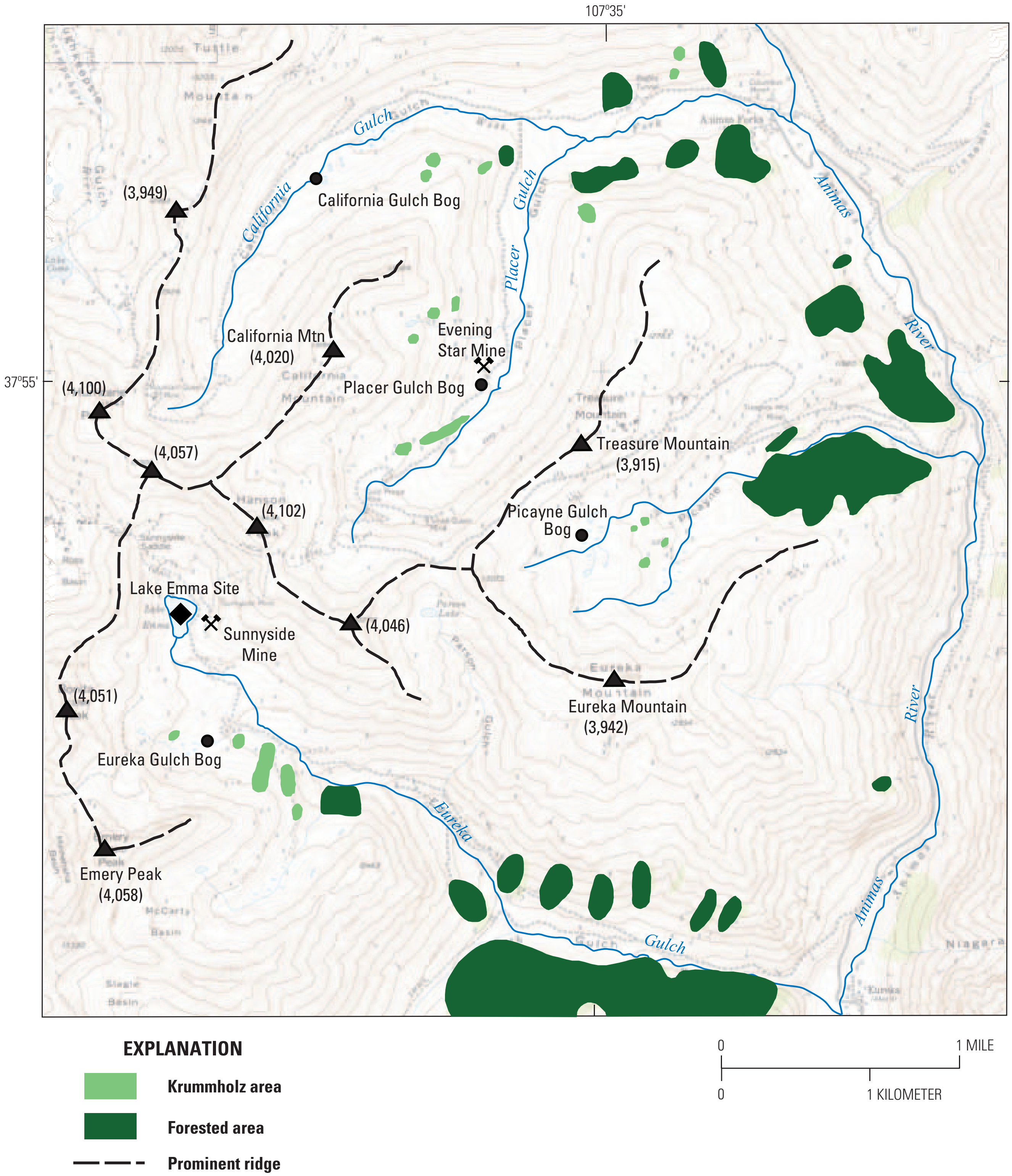


Figure 2. Study sites near headwater region of Animas River. Elevations in meters.

Snow can affect the position of timberline and treeline in several ways. Deep snow, melting late into the growing season, restricts the amount of time trees have to respond to the already short growing season (Jamieson and others, 1996). Conversely, snow may act as a protective blanket that shields young trees from the desiccating effects of winter winds. In some dry, windy areas, such as the Front Range in Colorado, windward slopes are swept free of snow, and the resulting lack of snow protection prevents trees from becoming established, thus lowering treeline (Arno and Hammerly, 1984).

Wind can also exert an important influence on the timberline and treeline ecotones. Strong winds can break branches and treetops as well as desiccate exposed trees. Wind-blown ice crystals can severely damage unprotected trees. Because the hardness of ice increases with decreasing temperature, during the winter trees are “sand blasted” by high winds and blowing snow (at 0°C ice has a hardness of 1.5 on the Mohs scale; at –70°C the hardness is 6 (Nesje and Dahl, 2000, p. 50)). The effects of desiccation and mechanical damage by wind are commonly seen in krummholz patches near treeline. The trees commonly have a “flagged” appearance—limbs are absent or dead on the windward side, whereas branches on the leeward side have living foliage (Jamieson and others, 1996; Brunstein, 2006).

Extreme examples of wind-blasted trees have been noted at various locations in the Colorado Front Range. At these locations bristlecone pines at their upper elevation limit have been stripped of bark on the windward (western) side, and the only living tissue is a strip of bark on the leeward side that supports several branches containing living foliage. In extreme examples the erosion caused by wind blasting has removed not only the bark on the windward side but also so much of the wood that the pith of the tree is no longer present (Brunstein, 2006).

In many areas, including the San Juan Mountains, timberline and treeline have been locally suppressed by frequent snow avalanches. Snow avalanches can scar or strip branches off trees and, if the avalanches are large enough, they can snap tree trunks (Carrara, 1979) and locally lower timberline on steep slopes and in high basins. In many cases the avalanche is confined by steep gullies along valley walls until it reaches the valley floor, where it spreads out and may represent a hazard to manmade structures. However, in intervening areas between avalanche gullies, timberline and treeline can reach their regional climatically controlled limits.

Climate

The San Juan Mountains are affected by air masses originating in several regions (fig. 3). Between October and May, air masses from the Pacific Ocean reach the San Juan Mountains. These air masses can originate in the Gulf of Alaska or off the coast of Baja California. Storms from this latter source bring the large amounts of snow for which the San Juan Mountains are noted.

Between July and September the San Juan Mountains are affected by the North American monsoon that brings frequent afternoon thunderstorms. At this time, communities in the San Juan Mountains receive about 30–35 percent of their annual precipitation (although higher elevations may receive proportionally more precipitation in the winter). During the monsoon, low-level moisture is drawn from the eastern tropical Pacific and Gulf of California by a thermal low in the desert southwest (Hales, 1972, 1974; Brenner, 1974; Adams and Comrie, 1997). In addition, air masses from the Gulf of Mexico may at times flow west across the highlands of Mexico and north along the Gulf of California, thereby contributing upper-level moisture and reinforcing the monsoonal circulation. Precipitation from the monsoon may continue into the late fall, usually through much of October (T.B. McKee, written commun., 1991).

Climatological records exist for several stations in the northern San Juan Mountains (table 1). However, because no permanent weather stations exist at or above timberline in this mountain range, values given for annual precipitation and for mean January and July temperatures were estimated. Precipitation values for timberline, treeline, and the Lake Emma site (table 1) were extrapolated from a lapse rate (79 centimeters per kilometer (cm/km)) derived between a station in the town of Silverton and one on Red Mountain Pass (fig. 1).

Mean January and July temperatures were estimated for timberline, treeline, and the Lake Emma site by extrapolation from the Red Mountain Pass station (table 1) and by using a winter lapse rate of 4.1 degrees Celsius per kilometer (°C/km) and a summer lapse rate of 6.2°C/km from the Colorado Front Range (Barry and Chorley, 1976). Regardless of the accuracy of these temperature estimates, harsh periglacial conditions in the higher regions of the San Juan Mountains are indicated by numerous active rock glaciers (Howe, 1909; Atwood and Mather, 1932; Carrara and Andrews, 1975; White, 1979), such as one on the northern flank of Emery Peak about 1 km south of the Lake Emma site (figs. 1, 4).

Acknowledgments

I thank the Sunnyside Gold Corporation, Silverton, Colo., for allowing access to the Lake Emma site. D.M. Cheney (U.S. Geological Survey, Denver, deceased) provided grain-size data. D.J. Christensen, J.T. Quirk, and A.C. Wiedenhoeft (Center for Wood Anatomy Research, U.S. Forest Service, Madison, Wisc.) identified many of the wood fragments collected in this study. E.A. Bikis (Wright Water Engineers, Denver) kindly provided wood fragments from the Telluride water well. Radiocarbon ages over the years were provided J.P. McGeehin, Meyer Rubin, and D.A. Trimble of the U.S. Geological Survey. J.A. Janssens (Limnological Research Center, University of Minnesota, Minneapolis) identified the mosses in the basal sediment of Lake Emma. I also thank W.N. Mode (University of Wisconsin at Oshkosh), K.L. Pierce (U.S. Geological Survey, Bozeman, Mont.) and S.A. Elias (Royal

Figure 3. Trajectories of major air masses that cross the San Juan Mountains, Colo. (after Hales, 1972, 1974; Brenner, 1974; Siemer, 1977; Callahan. 1986; Keen, 1987; and Adams and Comrie, 1997).

Table 1. Climate data from stations in the northern San Juan Mountains, Colo.

[°C, degree Celsius; °C/km, degree Celsius per kilometer; cm, centimeter; cm/km, centimeter per kilometer; m, meter]

Station location	Altitude (m)	Mean		
		Annual precipitation (cm)	January temperature (°C)	July temperature (°C)
Ouray[1]	2,390	58.5	–3.4	18.2
Telluride[1]	2,680	58.6	–6.0	15.1
Silverton[1]	2,825	62.4	–8.9	13.1
Red Mountain Pass[2]	3,415	109.2	–8.6	10.8
Timberline[3]	3,570[4]	121.5	–9.2	9.8
Treeline[3]	3,660	128.6	–9.6	9.3
Lake Emma[3]	3,740	134.9	–9.9	8.8

[1]Unpublished data accessed August 26, 2009, at *http://www.wrcc.dri.edu/summary/Climsmco.html*

[2]Data from Keen, 1996, p. 125.

[3]Precipitation values are estimates based on extrapolation of lapse rate between Silverton and Red Mountain Pass (79 cm/km). Temperature values are based on extrapolation from Red Mountain Pass using a winter lapse rate of 4.1°C/km, and a summer lapse rate of 6.2°C/km (Barry and Chorley, 1976). Both the precipitation and temperature estimates for timberline, treeline and Lake Emma and similar elevations are thought to be representative of the northern San Juan Mountains.

[4]Average of range of values given in text.

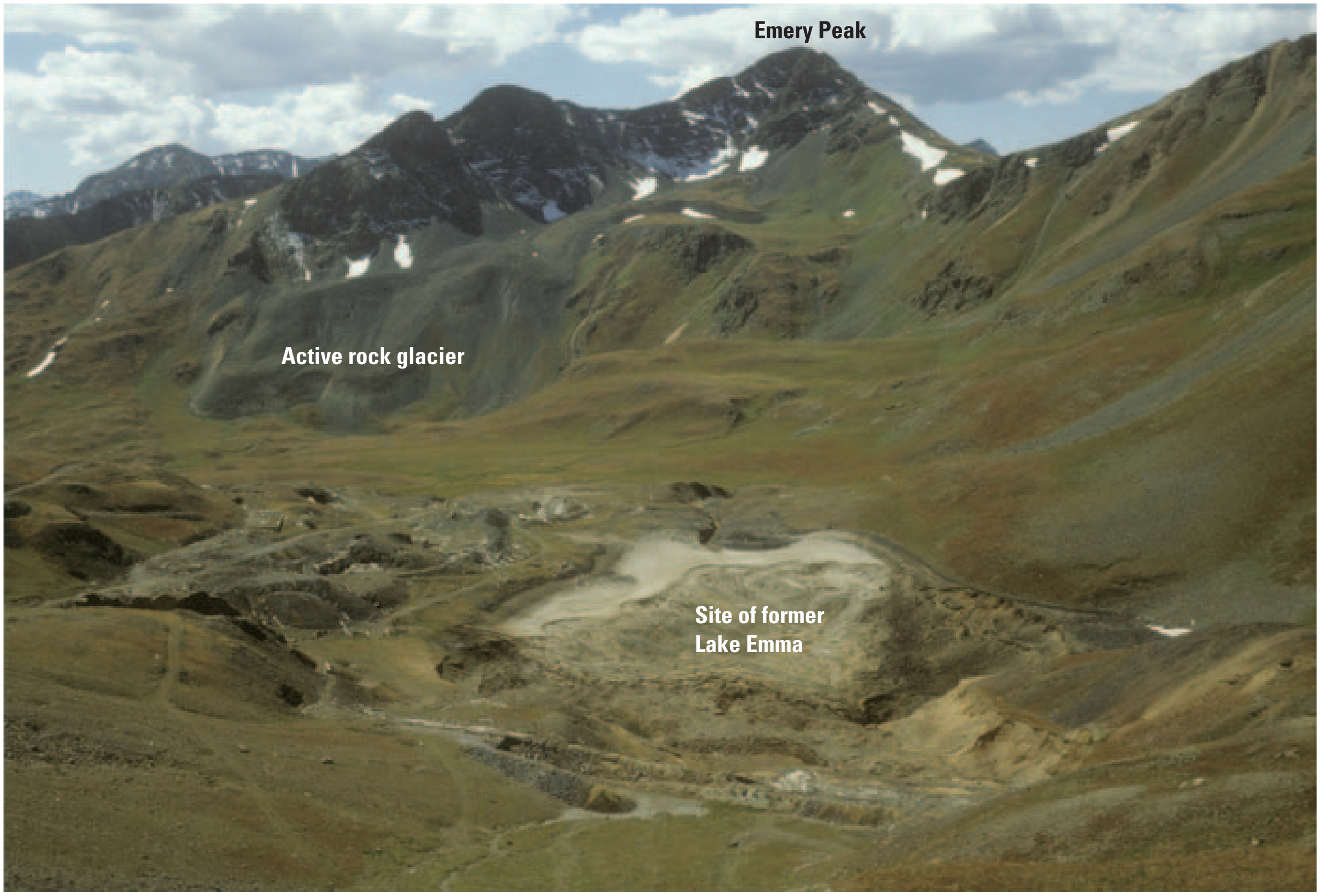


Figure 4. Site of former Lake Emma in 1979 after accidental drainage of the lake. Note an active rock glacier flowing from the cirque on Emery Peak about 1 km south of the former Lake Emma and the lack of coniferous trees, even krummholz forms.

Holloway College, University of London), who visited the Lake Emma site with the author in September 1979, September 1981, and August 1987, respectively, and S.P. Schilling (U.S. Geological Survey, Vancouver, Wash.) who visited most of the sites in this report in August 1985 and 1986. Their ideas and suggestions were greatly appreciated. Preliminary drafts of this report benefited substantially from reviews by P.L. Fall (Arizona State University, Tempe), R.W. Mathewes (Simon Fraser University, Burnaby, Canada), T.B. McKee (Colorado State University, Fort Collins) and L.E. Strickland, and R.S. Thompson (U.S. Geological Survey, Denver, Colo.), and M.M. Coates (ATA Services, Denver, Colo.).

Glacial Geology of the San Juan Mountains

Extent of Pinedale Glaciers

The San Juan Mountains were extensively glaciated during the Pleistocene as indicated by numerous cirques, broad U-shaped valleys, and moraines that emerge from canyons at the mountains' base (Howe, 1909; Atwood and Mather, 1932; Richmond, 1965; Gillam and others, 1984). Tills of three different ages were recognized in the San Juan Mountains by Atwood and Mather (1932). From oldest to youngest, these tills were termed the Cerro, Durango, and Wisconsin. However, after concluding that the type locality of the Cerro "till" is of landslide origin, Dickinson (1965) suggested that the term be abandoned.

From the limits of late Wisconsin (Pinedale) age deposits, as determined by Atwood and Mather (1932), the San Juan Mountains were covered by about 5,000 km^2 of glacial ice (fig. 5). Although Atwood and Mather (1932) inferred that most of the ice in the San Juan Mountains was in the form of valley glaciers, analysis of later large-scale topographic maps and air photos suggests that broad regional ice fields and transection glaciers existed as well (Porter and others, 1983). One of the largest of these ice bodies (1,300 km^2), the Animas-Uncompahgre transection glacier, was centered over the headwaters of the Animas River (fig. 1). The Animas glacier flowed south 65 km down the Animas River valley and formed a series of moraines near the present town of Durango

(Atwood and Mather, 1932; Richmond, 1965; Steven and others, 1974; Gillam and others, 1984). The Uncompahgre glacier flowed north 35 km along the valley of the Uncompahgre River (figs. 1, 5). Moraines from this glacier were formed about 3 km north of the town of Ridgway (Atwood and Mather, 1932; Steven and Hail, 1989) (fig. 5). The formation of Pinedale glaciers appears to have been initiated prior to 30,000 yr B.P. (about 35,000 cal yr) and were near their maximum extent about 22,000 yr B.P. (about 26,000 cal yr) (Benson et al., 2004).

Note: radiocarbon ages in this report are given in radiocarbon years before present (yr B.P.), and "present" is defined as 1950 A.D.; calibrated radiocarbon ages given in calendar years (cal yr) are from Fairbanks and others, 2005, and also set to 1950 A.D.; cosmogenic ages are labeled as ^{10}Be or ^{36}Cl ka and are set from the year they were dated.

Timing of Deglaciation

Radiocarbon Ages

Some of the oldest dates of Pinedale deglaciation from the Rocky Mountains have been reported from the San Juan Mountains. Molas Lake is located on a broad glaciated divide west of the Animas River valley at an elevation of 3,205 m (figs. 1, 6). During maximum Pinedale glaciation, this area was covered by several hundred meters of glacial ice. Radiocarbon ages of 15,450±220 yr B.P. (Y-1147) and 13,360±120 yr B.P. (Y-1437) were obtained from a 220-cm-long sediment core collected from this lake (Maher, 1961, 1972). The older radiocarbon age was obtained from organic sediment at a depth of 170–175 cm from a transition zone between underlying inorganic, laminated clay and overlying organic-rich sediment. The younger radiocarbon age was obtained from material at a depth of 142–147 cm at the base of the organic-rich sediment (Maher, 1972). The relation of the Molas Lake site to the Animas-Uncompahgre transection glacier indicates that when the Molas Lake site was deglaciated, at least half the glacier had melted (Porter and others, 1983). Hence, the radiocarbon age from Molas Lake could indicate extensive deglaciation within the San Juan Mountains before 15,500 yr B.P. (about 18,700 cal yr). However, because Molas Lake is underlain by Paleozoic limestone the radiocarbon ages from this lake may have been subject to a "hard-water effect," and hence may be older than the true age of the sediment analyzed (L.J. Maher Jr., oral commun., 1983).

Lake Emma, at an elevation of 3,740 m, is located above present-day treeline in a south-facing cirque, near the headwaters of the Animas River (figs. 1, 4, 5). It was accidentally drained in 1978 when the roof of an underlying mine stope collapsed. Radiocarbon ages of 14,900±250 yr B.P. (W-4209), 14,130±150 yr B.P. (W-4289), and 14,940±140 yr B.P. (W-4525) (fig. 7) were obtained from moss fragments from the basal organic sediment of Lake Emma (Carrara and others, 1984). Because Lake Emma is underlain by a noncarbonate-bearing volcanic rock and the moss fragments were determined to be from terrestrial moss (J.A. Janssens, written commun., 1982), the radiocarbon ages were initially thought to be accurate. Because the Lake Emma site lies near the center of the former Animas-Uncompahgre transection glacier, these ages were originally interpreted as indicating that the glacier, one of the largest in the southern Rocky Mountains, no longer existed by 15,000 yr B.P. (about 18,100 cal yr) (Carrara and others, 1984). However, subsequent work by Elias and others (1991) indicated that the radiocarbon ages of mosses from the Lake Emma site must also be viewed with suspicion. Radiocarbon ages (obtained mostly by accelerator mass spectrometry (AMS)) from wood fragments and insect fossils from the same horizons as the mosses yielded radiocarbon ages 3,500 to 6,000 years younger than the moss ages (Elias and others, 1991) (fig. 7).

Disregarding the moss ages, the oldest radiocarbon age from the high regions of the San Juan Mountains is from a bog in a cirque near Hurricane Basin (figs. 1, 5). Here a radiocarbon age of 9,620±440 yr B.P. (St-3909) (about 11,000 cal yr) (fig. 8) was obtained from organic material concentrated from relatively inorganic clay (Andrews and others, 1975). Other similar ages have been obtained from the Lake Emma site (fig. 7). A willow fragment from Lake Emma sediments yielded an AMS radiocarbon age of 9,400±70 yr B.P. (AA-3888) (about 10,600 cal yr). The oldest reliable radiocarbon age of a conifer fragment from the Lake Emma site is now believed to be the 9,220±120 yr B.P. age (W-4524) (about 10,400 cal yr) (table 2) obtained from a spruce fragment in a section sampled for pollen analysis (Carrara and others, 1984). The radiocarbon age of this spruce fragment represents an interval of higher than present-day treeline and therefore may postdate deglaciation by a considerable period, possibly several of thousands of years.

Cosmogenic Ages

Cosmogenic dating of glacially polished bedrock surfaces in the Animas River valley indicates that glacial retreat from the Pinedale terminal position, several kilometers north of the present-day town of Durango (fig. 5), began about 19.4±1.5 ^{10}Be ka (about 16,300 yr B.P.) (Guido and others, 2007). This study investigated various sites from near the terminal position upvalley to near the town of Silverton (figs. 1, 5) and concluded that retreat proceeded at an average rate of 15.4 meters per year (m/yr). A cosmogenic age of 12.3±1.0 ^{10}Be ka (about 10,450 yr B.P.), which was obtained from a glacially polished bedrock surface near Highland Mary Lakes (fig. 9) at an elevation of 3,704 m near the Continental Divide, indicates that by this time deglaciation of the San Juan Mountains was essentially complete (Guido and others, 2007). Although the locality of the dated sample is about 500 m higher in elevation than Molas Lake, the age from this sample is considered a more reliable estimate of the timing of regional

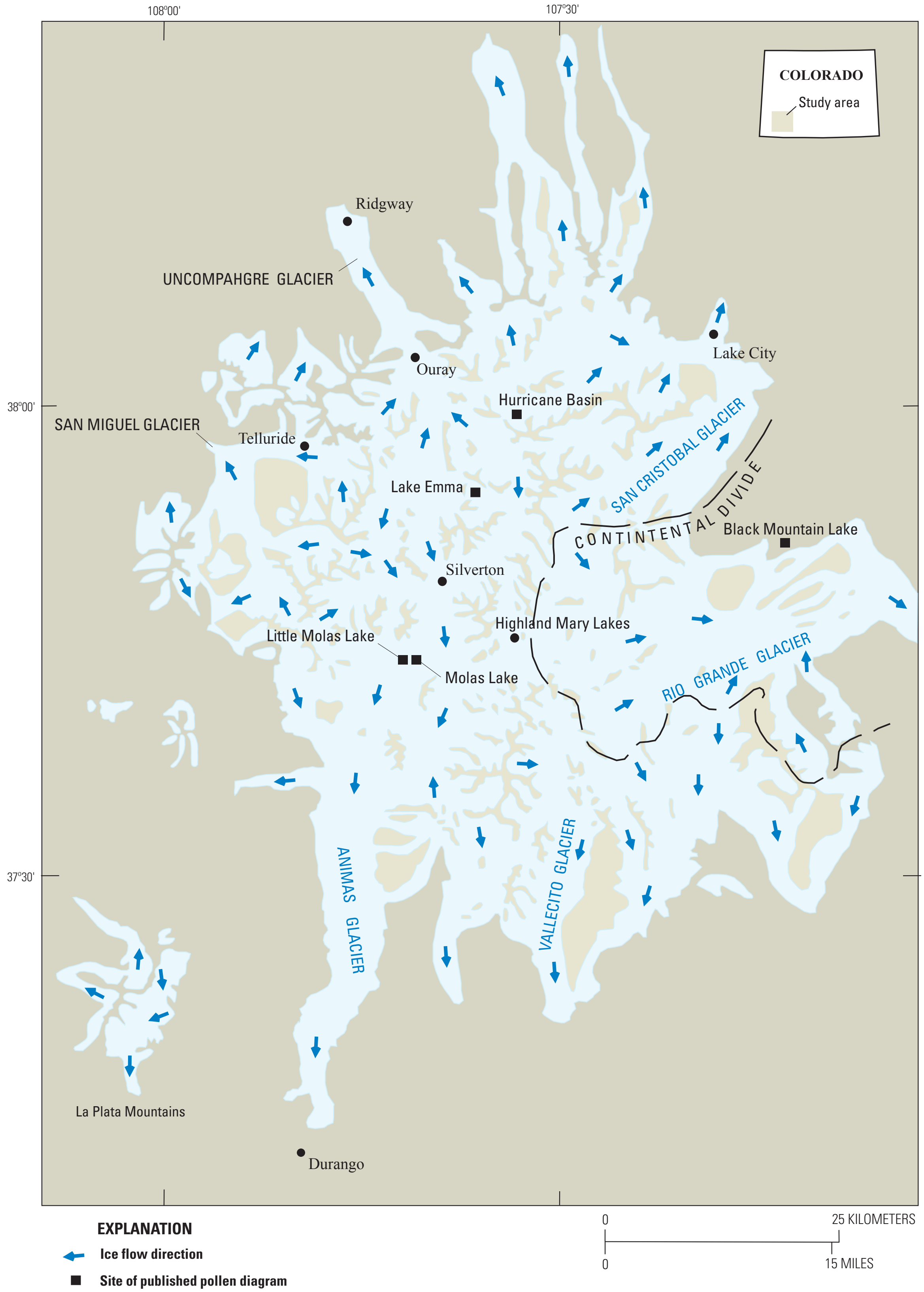


Figure 5. Limits of Wisconsin (Pinedale) glaciation in western San Juan Mountains (after Atwood and Mather, 1932), including the Animas-Uncompahgre transection glacier. This glacier stretched from near the present-day town of Ridgway south for about 100 km to near the present-day town of Durango.

Figure 6. Molas Lake area, located on a broad glaciated divide west of the Animas River valley. Elevation 3,205 meters.

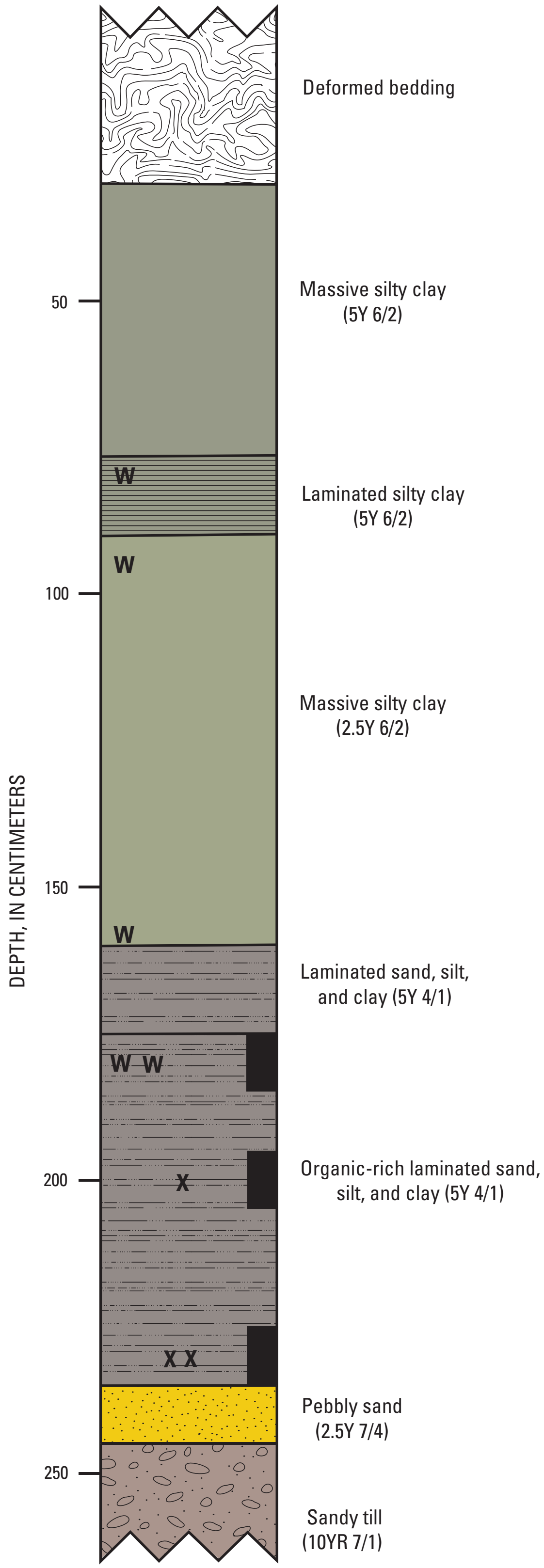
deglaciation than the radiocarbon ages from Molas Lake or the radiocarbon ages of moss fragments from Lake Emma.

Similar ages of initial deglaciation were obtained from sites in the Rio Grande drainage (Benson and others, 2005). The Rio Grande glacier (fig. 5), which covered about 1,000 km^2 and was about 60 km long, also emerged from the ice mass that covered the San Juan Mountains. Cosmogenic dating of boulders from the terminal moraine deposited by the Rio Grande glacier and the nearby Red Mountain glacier to the south (Atwood and Mather, 1932) yielded a mean age of 18.9 ^{36}Cl ka (about 15,700 yr B.P.) (Benson and others, 2005).

Cirque Moraines and Present-Day Snowfields

Two sets of late Pleistocene cirque moraines were found in the San Juan Mountains (Andrews and others, 1975; Carrara and Andrews, 1975). The older set (designated as the Yankee Boy moraines (fig. 10) because of the excellent examples in Yankee Boy Basin (fig. 1)) is widespread throughout the study area. These moraines range in elevation from 3,350 to 3,780 m (average 3,635 m) and are commonly found in cirques oriented N. 85° W. to N. 100° E. The distance between these moraines and the cirque headwall ranges from 0.4 to 2 km; distances of 0.8–1 km are the most common. The crests of these moraines are commonly 15 m wide but may be as little as 5 m, and are commonly overlain by 10 cm of loess. Depth of stream dissection through the terminal arc is usually about 10 m. These moraines are commonly situated in cirques underlain by Tertiary andesitic flows and ashes that are very susceptible to weathering.

The younger set of moraines is designated as the Grenadier moraines (fig. 11) because these moraines have been found only at the northern base of the Grenadier Range (fig. 1). The moraines range in elevation from 3,640 to 3,780 m (average 3,730 m) and are commonly found in cirques oriented from north to N. 40° E. Moraines of this



Radiocarbon ages (yr B.P.) of wood, fossil insects, and moss fragments from the stratigraphic sections sampled at Lake Emma.

Wood (W)	Insect (X)	Moss ■
5,440±100		
6,670±70		
8,625±90		
9,220±120 9,400±70		12,900±200
	8,200±160	13,580±200
	8,940±85 9,020±80	14,130±150 14,900±250 14,940±140

Figure 7. Composite stratigraphic section at the Lake Emma site (after Carrara and others, 1984; and Elias and others, 1991) showing radiocarbon ages (yr. B.P.) of wood, insect fossils, and detrital moss.

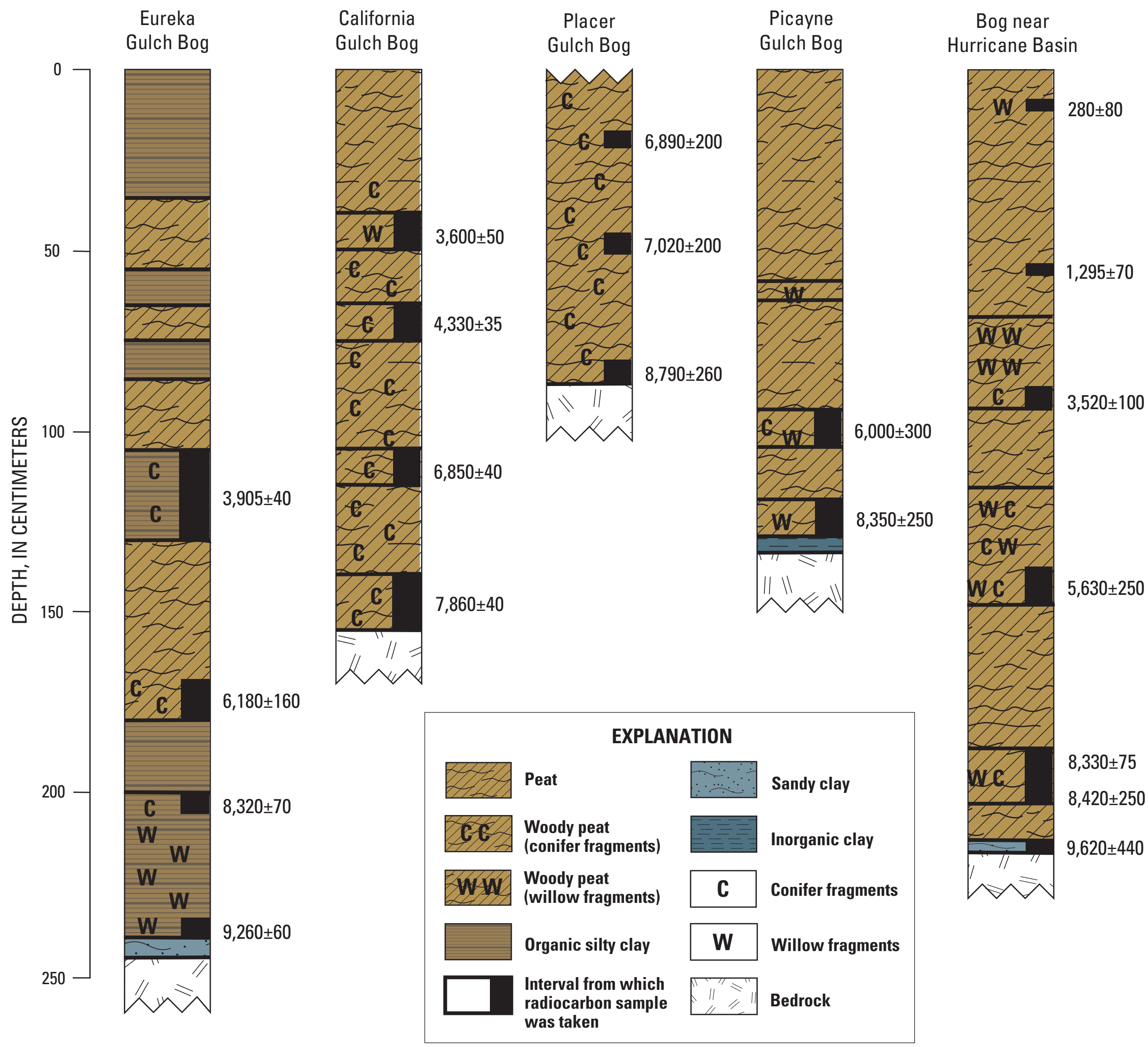


Figure 8. Stratigraphic sections and radiocarbon ages (yr B.P.) from bogs in the northern San Juan Mountains. The section for the bog near Hurricane Basin represents a composite stratigraphy from Andrews and others (1975) and Carrara and others (1991).

Table 2. Radiocarbon ages of coniferous wood fragments from the Lake Emma site, northern San Juan Mountains, Colo.

[Elevation of Lake Emma site is 3,740 m. The 66 radiocarbon ages from 53 coniferous wood fragments here presented include 25 previously unpublished ages. Ages of samples shown in the same color were obtained from the same wood fragment. A, genus Abies (fir); P, genus Picea (spruce); Lk, Lake; AA, National Science Foundation–Arizona AMS Facility, University of Arizona, Tucson; DIC, Dicarb Radioisotope Laboratory, Chagrin Falls, Ohio; USGS, U.S. Geological Survey, Menlo Park, Calif.; W, U.S. Geological Survey, Reston, Va.; WW, U.S. Geological Survey, Reston, Va.; ≈, approximately equal to]

No.	^{14}C age (yr B.P.)	Laboratory ID	Calendar yr (cal yr)[a]	Field ID	Genus	Number of rings	Weight (gm)
01	3075±35	USGS–2617	3304±46	Stand Metals 01–78	P	60	≈1,500
02	3120±80	W–4242	3339±86	Stand Metals 01–78	P	60	≈1,500
03	**5370±110	USGS–3005	6158±130	Lk Emma 04–86	P	34	69
04	5420±200	W–5616	6201±215	Lk Emma 09–83	P	≈75	2,530
05	5440±100	USGS–2135	6235±103	LE Pollen (81)–79	A?	10	2
06	5570±70	W–4680	6349±64	Lk Emma 04–79	P	67	≈100
07	5755±45	USGS–1340	6546±64	Lk Emma 11–79	A	31	40
08	**5839±40	*WW–6118	6652±44	Lk Emma 04–79	P	67	≈100
09	**5858±40	*WW–6115	6671±42	Lk Emma 04–86	P	34	69
10	**5870±30	*WW–6593	6683±31	Lk Emma 09–83	P	≈75	2,530
11	5950±100	W–4682	6776±122	Lk Emma 05–79	A	29	≈100
12	**6020±70	USGS–3003	6860±92	Lk Emma 02–86	P	70	164
13	6170±70	W–4676	7064±103	Lk Emma 01–79	P	44	≈50
14	6300±280	W–5613	7186±302	Lk Emma 06–83	P	≈100	439
15	6330±110	W–4686	7252±119	Lk Emma 08–79	P	67	≈80
16	6670±70	W–4523	7545±55	LE Pollen (96)–79	P	23	≈20
17	6690±60	USGS–2472	7561±46	Lk Emma 08–85	P	46	103
18	6870±65	DIC–3163	7695±59	Lk Emma 02–83	P	24	77
19	6995±40	USGS–2312	7828±50	Lk Emma 07-85	P	43	327
20	7010±40	USGS–2471	7845±49	Lk Emma 06–85	P	≈40	170
21	7400±40	USGS–2313	8218±52	Lk Emma 10–85	P	≈60	214
22	**7430±70	USGS–3006	8255±80	Lk Emma 05–86	P	≈40	225
23	**7550±70	USGS–3004	8366±53	Lk Emma 03–86	P	29	41
24	7620±100	USGS–2616	8417±81	Lk Emma 09–85	P	≈35	57
25	7670±75	DIC–2895	8454±65	Lk Emma 10–83	P	?	430
26	**7730±40	USGS–3183	8507±46	Lk Emma 03–87	P	25	242
27	7780±100	W–4678	8562±114	Lk Emma 03–79	P	63	≈100
28	7780±320	W–5608	8620±374	Lk Emma 01–83	P	≈30	112
29	7810±120	W–4243	8604±153	Stand Metals 02–78	A	33	≈500
30	**7820±30	*WW–6592	8591±26	Lk Emma 01–87	P	21	375
31	**7830±50	USGS–2827	8602±52	Lk Emma 02–85	P	≈25	32
32	7850±90	W–5674	8643±129	Lk Emma 07–79	P	48	≈1,000
33	7870±90	W–4684	8671±139	Lk Emma 07–79	P	48	≈1,000
34	7870±110	USGS–1339	8679±164	Lk Emma 10–79	P	23	73
35	**7900±80	USGS–3007	8712±141	Lk Emma 06–86	P	18	20
36	**7920±45	USGS–2828	8730±106	Lk Emma 03–85	P	≈30	50
37	7970±90	USGS–1344	8834±161	Lk Emma 15–79	P	15	16
38	8010±80	USGS–1346	8904±139	Lk Emma 18–81	P	150	≈5,000
39	**8040±50	*WW–962	8967±74	Lk Emma 04–85B	P	28	46

Table 2. Radiocarbon ages of coniferous wood fragments from the Lake Emma site, northern San Juan Mountains, Colo.—Continued

[Elevation of Lake Emma site is 3,740 m. The 66 radiocarbon ages from 53 coniferous wood fragments here presented include 25 previously unpublished ages. Ages of samples shown in the same color were obtained from the same wood fragment. A, genus Abies (fir); P, genus Picea (spruce); Lk, Lake; AA, National Science Foundation–Arizona AMS Facility, University of Arizona, Tucson; DIC, Dicarb Radioisotope Laboratory, Chagrin Falls, Ohio; USGS, U.S. Geological Survey, Menlo Park, Calif.; W, U.S. Geological Survey, Reston, Va.; WW, U.S. Geological Survey, Reston, Va.; ≈, approximately equal to]

No.	^{14}C age (yr B.P.)	Laboratory ID	Calendar yr (cal yr)[a]	Field ID	Genus	Number of rings	Weight (gm)
40	8040±120	W–4677	8937±183	Lk Emma 02–79	P	56	≈100
41	**8070±50	*WW–963	8998±54	Lk Emma 04–85C	P	28	≈100
42	**8095±45	USGS–3182	9019±41	Lk Emma 02–87	P	65	247
43	8100±70	DIC-2893	9026±85	Lk Emma 04-83	P	≈30	180
44	**8190±50	*WW-728	9131±81	Lk Emma 04-85	P	28	0.57
45	8260±40	USGS-2314	9246±74	Lk Emma 11-85	P	57	465
46	8310±75	DIC-2894	9319±112	Lk Emma 07-83	A	≈50	410
47	8370±135	DIC-2197	9371±153	Lk Emma 17-80	P	17	9
48	8520±80	USGS-1342	9510±48	Lk Emma 13-79	P	51	61
49	8520±80	DIC-3164	9510±48	Lk Emma 03-83	P	≈15	32
50	**8590±60	USGS-3002	9546±36	Lk Emma 01-86	P	≈60	42
51	8625±90	*AA-3889	9581±88	LE Fos Insect 02-87	P	4	0.6
52	**8640±50	USGS-2826	9575±45	Lk Emma 01-85	P	≈30	47
53	**8656±50	*WW-5548	9589±52	Lk Emma 16-80	P	20	28
54	8730±90	W-4685	9711±156	Lk Emma 06-79	P	35	≈100
55	**8772±47	*WW-6119	9765±108	Lk Emma 06-79	P	35	≈100
56	**8796±57	*WW-6117	9822±138	Lk Emma 14-79	P	55	25
57	8810±80	USGS-1343	9857±176	Lk Emma 14-79	P	55	25
58	**8820±50	USGS-2830	9877±133	Lk Emma 05-85	P	≈45	71
59	**8855±51	*WW-5547	9959±134	Lk Emma 05-83	P	25	181
60	**8872±47	*WW-6116	9998±122	Lk Emma 05-85	P	≈45	71
61	8910±100	USGS-1338	10,041±177	Lk Emma 09-79	A	47	43
62	**8950±45	USGS-3181	10,139±81	Lk Emma 01-87	P	21	375
63	9000±300	W-5611	10,123±399	Lk Emma 05-83	P	25	181
64	9220±120	W-4524	10,391±154	LE Pollen (161)-79	P	83	≈20
65	9520±90	USGS-1345	10,817±174	Lk Emma 16-80	P	20	28
66	9580±130	USGS-1341	10,921±222	Lk Emma 12-79	P	19	32

[a]Data accessed March 20, 2009 at *http://www.radiocarbon.LDEO.columbia.edu*. See Fairbanks, R.G. and others, 2005, Marine radiocarbon calibration curve spanning 0 to 50,000 years B.P., based on paired 230Th/234U/238U and 14C dates on pristine corals: Quaternary Science Reviews, v. 24, p. 1781–1796.

[*]Accelerator mass spectrometry radiocarbon age (n=13).

[**]Previously unpublished radiocarbon ages (n=25).

Figure 9. Highland Mary Lakes area from which a cosmogenic age of deglaciation of 12.3±1.0 ^{10}Be ka was obtained (Guido and others, 2007).

Figure 10. Yankee Boy moraine in Yankee Boy Basin.

Figure 11. Grenadier moraine at the northern base of the Grenadier Range.

group are usually found within 450 m of the cirque headwall. Moraine crests are usually no more than 5 m wide, and only one moraine of this group has been dissected by a stream. These moraines are in cirques underlain by the Precambrian Uncompahgre Formation, which consists of interlayered quartzite and slate (Barker, 1969), which are very resistant to weathering.

The exact ages of these two sets of moraines are not known. No datable organic material has been found in association with either set of moraines. Furthermore, differences in lithology make problematic the use of relative weathering criteria to differentiate the two moraine sets.

The two sets of moraines are distinguished on the basis of two criteria: the downvalley distance between the cirque headwall and moraine (S), and the ratio of the distance between the cirque headwall and moraine to the relief between the moraine crest and top of headwall (R). As mentioned above, Yankee Boy moraines are found 0.4–2 km from their cirque headwalls; distances of 0.8 to 1 km are most common. Grenadier moraines are usually found about 450 m from their cirque headwall. The difference between the two sets of moraines is even more striking when their S/R ratios are compared. This S/R ratio is a function, at least in part, of the severity of the climate that produced the former glaciers. The average S/R value for Yankee Boy moraines is 3.57:1, whereas the average value for Grenadier moraines is 1.46:1. In the case of Grenadier moraines a given amount of shading by the cirque headwall produced significantly smaller glaciers than was the case with Yankee Boy moraines. This relation suggests that the two sets of moraines formed under different climatic conditions and hence at different times.

Both the Yankee Boy and Grenadier moraines, as well as other correlative deposits (rock glaciers and protalus ramparts) found in the San Juan Mountains are thought to be late Pleistocene in age (Carrara and others, 1984). As will be discussed later in this report, radiocarbon ages of coniferous wood from Lake Emma clearly indicate that, by at least 9,200 yr B.P. (about 10,400 cal yr), summer temperatures were higher than at present and thus both sets of moraines must have been deposited before that time. Although both moraine sets are found mostly in north-facing cirques (Carrara and Andrews, 1975), and Lake Emma is in a south-facing cirque, it is climatically incompatible that small glaciers lingered in north-facing cirques during a period of warmer than present-day summer temperatures. Cosmogenic dating of rock surfaces indicatesthat deglaciation in the Animas River drainage was essentially complete by 12.3±1.0 ^{10}Be ka (about 10,450 yr B.P.) (Guido and others, 2007) and suggests that at least Yankee Boy moraines were probably deposited by that time.

Yankee Boy moraines represent a regional period of moraine formation throughout the northern San Juan Mountains. These moraines are thought to correlate with the Satanta Peak moraines of the Colorado Front Range (Benedict, 1973, 1985), and the Temple Lake moraine of the Wind River Range, Wyoming (Davis, 1988) and are probably Younger Dryas in age (11,000–10,000 yr B.P. (about 12,800–11,500 cal yr)). Grenadier moraines probably formed a short time after the Yankee Boy moraines and represent the product of remnant glacier ice lying in well-insulated niches in a mountain range undergoing rapid deglaciation.

Although the San Juan Mountains are generally higher than the Colorado Front Range, which contains small glaciers and snowfields fronted by neoglacial moraines (Outcalt and MacPhail, 1965), the San Juan Mountains contain few permanent snowfields and no present-day glaciers. Only two snowfields of any consequence have been noted by the author; one, at the northern base of the Trinity Peaks in the Grenadier Range (figs. 1, 12), appears to be fronted by a Little Ice Age moraine. Another snowfield is present in a northwest-facing cirque about 1 km northeast of Mount Wilson (fig. 1). Thus it appears that the higher snowfalls of the San Juan Mountains are offset by a longer melt season or more southerly latitude compared with the Front Range. The San Juan Mountains are also less windy than the Front Range, where wind drifting is thought to be responsible for the presence of many of the small glaciers (Outcalt and MacPhail, 1965; Hoffman and others, 2007).

Postglacial Forestation and Holocene Treeline in the Northern San Juan Mountains

Introduction

Ten sites in the northern San Juan Mountains have yielded information about postglacial forestation and Holocene treeline fluctuations. Many of these sites are the subject of reports: Maher (1961, 1963, 1972), Andrews and others (1975), Elias (1982), Carrara and others (1984, 1991), Elias and others (1991), Reasoner and Jodry (2000), and Toney and Anderson (2006). This information consists primarily of pollen analyses of radiocarbon-dated sediment cores, but it also includes sites where coniferous wood fragments and fossil insects were recovered and radiocarbon dated. Because the coniferous wood fragments recovered from these sites originated at higher elevations and were carried downslope to be deposited, the elevation of these sites represent the minimum elevation at which these recovered coniferous wood fragments originally grew.

The following section synthesizes

1. Previously published information,
2. Unpublished radiocarbon ages of coniferous wood fragments from a water well drilled near the town of Telluride in 1991, and
3. Unpublished radiocarbon ages of coniferous wood fragments, including AMS radiocarbon ages, from the Lake Emma site (these ages require a moderate revision of previous interpretations) (Carrara and others, 1984, 1991).

Figure 12. Snowfield at the northern base of Trinity Peaks in the Grenadier Range. Snowfield appears to be fronted by a Little Ice Age moraine; an active rock glacier is in the foreground.

The sites are discussed in order of increasing elevation. In addition to those sites in the San Juan Mountains, approximately 20 other sites throughout western North America that have yielded conifer remains above present-day limits demonstrating treelines higher than at present throughout much of the Holocene are presented in the appendix at the end of this report.

Telluride Water Well (2,665 m asl)

A well that was drilled immediately southwest of the town of Telluride (fig. 1) provides evidence of the forestation of the San Juan Mountains after deglaciation. The well, at an elevation of 2,665 m, was drilled though the floodplain of the San Miguel River to bedrock at a depth of 33.5 m (fig. 13). The interval between depths of 18.3 and 22.9 m contained abundant coniferous wood fragments identified as spruce (D.J. Christensen, Center for Wood Anatomy Research, written commun., 1992). Conventional radiocarbon dating of these wood fragments yielded ages of 10,870±110 yr B.P. (W–6405) from wood fragments between depths of 18.3 and 19.8 m; 11,000±110 yr B.P. (W–6407) from wood fragments between depths of 19.8 and 21.3 m; and 11,840±120 yr B.P. (W–6409) from wood fragments between depths of 21.3 and 22.9 m (table 3). A subsequent AMS radiocarbon date obtained from wood fragments in the lower interval yielded an age of 10,906±54 yr B.P. (WW–6114). This date suggests that the age obtained for sample W–6409 may be in error by approximately 800 radiocarbon years and that the entire interval between depths of 18.3 and 22.9 m may have been rapidly deposited about 11,000 yr B.P. (about 12,900 cal yr).

Two additional AMS radiocarbon ages were obtained at greater depth in the core; their interpretation is problematic. In the interval between 25.9 and 27.4 m, a spruce fragment (D.J. Christensen, Center for Wood Anatomy Research, written commun., 1992) was recovered. This fragment yielded an AMS radiocarbon age of 10,972±127 yr B.P. (AA–9533) and, because this age is no older than the radiocarbon ages between 18.3 and 22.9 m, it may represent downhole contamination. Finally, in the interval between 32 and 33.5 m, another small spruce fragment (D.J. Christensen, Center for Wood Anatomy Research, written commun., 1992) was recovered. This fragment yielded an AMS radiocarbon age of 11,219±100 yr B.P. (AA–9532) and again may represent downhole contamination.

Conversely, if the lower two radiocarbon ages do not represent downhole contamination, then because 5 of the 6 radiocarbon ages obtained from the Telluride water well site overlap at 2σ (standard deviations) (W–6409 is the exception), then the entire sediment column from 18.3 m down to the bedrock base at 33.5 m depth may have been rapidly deposited about 12,900 cal yr.

The Telluride water well is located about 10 km upvalley from the Pinedale-age terminal moraines of the San Miguel glacier (Atwood and Mather, 1932) (fig. 5). Hence, the radiocarbon ages of coniferous wood fragments from the well site clearly indicate substantial deglaciation before about 11,000 yr B.P. (about 12,900 cal yr) and the establishment of forest in a formerly glaciated valley. The exact position of timberline during this time is not known, because these wood fragments may have been washed down from higher elevations and deposited at the site of the water well. All that can be concluded is that timberline was no more than about 900 m below its present-day limit and possibly much less.

Table 3. Radiocarbon ages from spruce fragments recovered from Telluride, Colo., water well.

[cal yr, calendar year; m, meter; yr B.P., year before present]

Depth (m)	Laboratory number	^{14}C Age (yr B.P.)	Calendar age (cal yr)[a]
18.3–19.8	W–6405	10,870±110	12,771±93
19.8–21.3	W–6407	11,000±110	12,875±95
21.3–22.9	W–6409	11,840±120	13,682±109
	WW–6114	10,906±54[b]	12,798±54
25.9–27.4	AA–9533	10,972±127[b]	12,853±107
32.0–33.5	AA–9532	11,219±100[b]	13,062±99

[a]Data accessed on the World Wide Web at *http://www.radiocarbon.LDEO.columbia.edu* on March 20, 2009. See Fairbanks, R.G and others 2005, Marine radiocarbon calibration curve spanning 0 to 50,000 years B.P., based on paired ^{230}Th/^{234}U/^{238}U and ^{14}C dates on pristine corals: Quaternary Science Reviews, v. 24, p. 1781–1796.

[b]Radiocarbon age determined by accelerator mass spectrometry.

Molas Lake (3,205 m asl)

Molas Lake, at an elevation of 3,205 m, is about 400 m below present-day timberline. The lake is about 7 km south of the town of Silverton (fig. 1) on a broad divide (fig. 6) between the Animas River and Lime Creek. The lake has a surface area of about 0.07 km^2 and is probably no more than several meters deep. As previously mentioned, a core 220 cm in length was collected from Molas Lake for pollen analysis (Maher, 1961, 1972).

The stratigraphy of the core is such that it can be divided into three sections. The lowest section (below 175 cm) consisted of greenish-gray, inorganic, laminated silts and clays. Between 175 and 145 cm the core consisted of light brown, calcareous gyttja that represents a transition zone between the underlying inorganic silts and clays and the overlying (above 145 cm depth) dark brown gyttja (Maher, 1961).

The pollen spectra from the inorganic sediment (below 175 cm) at Molas Lake are dominated by high values of *Artemisia* spp. and low values or absence of tree pollen (Maher, 1961). Percentages of *Artemisia* spp. pollen ranges from about 45 to 65 percent, whereas total nonarboreal pollen ranges from about 60 to 75 percent. *Picea* spp. and *Pinus* spp. pollen abundances range from about 1 to 10 percent and 18 to 35 percent,

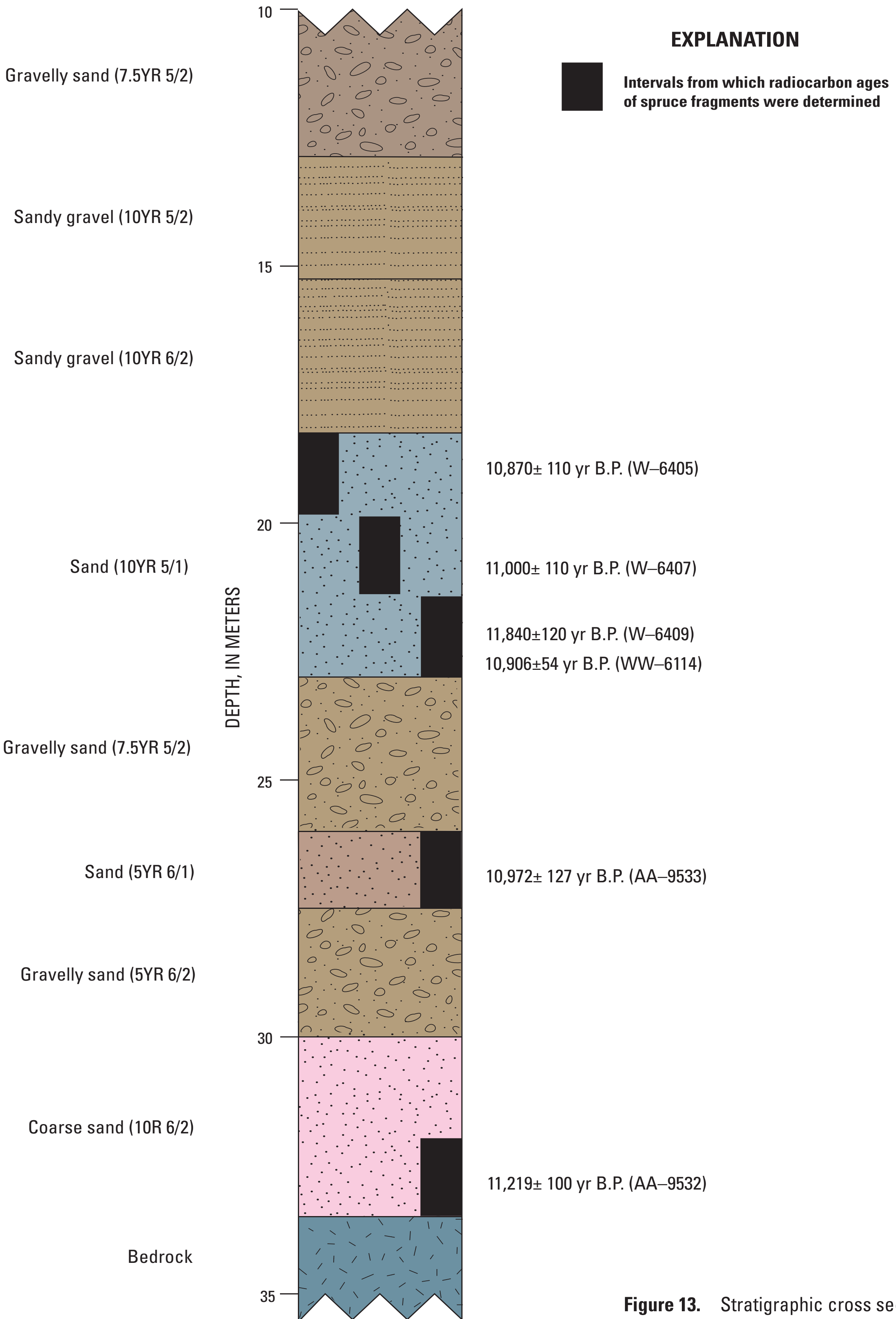


Figure 13. Stratigraphic cross section and radiocarbon ages (yr B.P.) from the Telluride water well.

respectively. Because these inorganic sediments consist of finely laminated silty layers, they were probably deposited soon after deglaciation and before vegetation was established around the site (Maher, 1961). Because of the possible hard-water contamination of the radiocarbon ages obtained from this core, which yielded ages older than the actual age of the sediment, the cosmogenic age of 12.3±1.0 ^{10}Be ka (about 10,450 yr B.P obtained from a glacially polished bedrock surface near Highland Mary Lakes (Guido and others, 2007), approximately 500 m higher in elevation than Molas Lake, is thought to represent a closer minimum date of deglaciation for the Molas Lake area.

The pollen spectra in the interval between 147 and 175 cm depth, represent a transition zone between the underlying postglacial inorganic sediments and the overlying organic-rich sediments. This interval has lower values of nonarboreal pollen and higher values of tree pollen than the underlying sediments. Pollen data including spruce/pine pollen ratios indicate that, when Molas Lake first began accumulating organic sediment, the average July temperature was about 5°C cooler and timberline about 650 m lower than at present (Maher, 1961). This finding places timberline at an elevation of about 2,885 m at that time. Unfortunately, as previously mentioned, the radiocarbon age (13,360±120 yr B.P., Y–1437) obtained from material at the base of the organic-rich sediment in Maher's (1961) core must be viewed with suspicion (L.J. Maher, Jr., oral commun., 1983).

The pollen spectra from the organic-rich sediment above 147 cm resemble the modern pollen spectra from the site. *Artemisia* spp. pollen is about 10 percent throughout this section, whereas total nonarboreal pollen ranges from about 10 to 35 percent. *Picea* spp. and *Pinus* spp. pollen ranges from about 15 to 45 percent and 15 to 65 percent, respectively. Also in this interval, at about 125 cm, nonarboreal pollen reaches its lowest value (about 10 percent), whereas *Picea* spp. and *Pinus* spp. are quite abundant (about 30 and 55 percent respectively). Maher (1961) concluded that some time during this period the maximum postglacial July temperature was about 2°C warmer than at present. Because the modern pollen spectra appear to have been established by about 9,000 yr B.P. at the Hurricane Basin and Little Molas Lake sites (figs. 1, 5), and probably about that same time at the Lake Emma site (discussed below), it is suggested here that the base of the organic-rich sediment at Molas Lake (147 cm depth) also dates to about 9,000 yr B.P. (about 10,150 cal yr).

Little Molas Lake (3,370 m asl)

Little Molas Lake, about 2 km west of Molas Lake (fig. 1), lies at an elevation of 3,370 m, about 230 m below present-day timberline. Two sediment cores 4.5 m long and a short core less than 1 m long, which sampled the upper unconsolidated sediments at the sediment-water interface, were collected from Little Molas Lake for pollen analysis (Toney and Anderson, 2006). Although this lake, like Molas Lake, is underlain by Paleozoic limestone, radiocarbon ages obtained from discrete macrofossils such as spruce needles, bark, and seeds and insect remains provide a reliable chronology. Seven radiocarbon ages were obtained from one of the long cores. A radiocarbon age of about 11,200 cal yr was obtained from remains of aquatic insects near the base of the core at a depth of 409–412 cm (Toney and Anderson, 2006). The pollen and macrofossil data were interpreted as indicating that the replacement of tundra vegetation by spruce forest corresponded with the end of the Younger Dryas, about 10,000 yr B.P. (about 11,500 cal yr) (Toney and Anderson, 2006). At this time an increase in *Diploxylon* pollen (compare with *P. ponderosa*) was interpreted as indicating the influence of the southwestern monsoon. In addition, the pollen and macrofossil data indicated that spruce and other conifers have grown near Little Molas Lake throughout the Holocene (Toney and Anderson, 2006).

Black Mountain Lake (3,413 m asl)

Black Mountain Lake, in the Rio Grande drainage east of the Continental Divide (figs. 1, 5), lies at an elevation of 3,413 m about 100–150 m below present-day timberline (Reasoner and Jodry, 2000). Although the Black Mountain Lake site was not glaciated during the Pinedale glaciation, it is located on a hillside above Pinedale-age deposits (M.A. Reasoner, oral commun., 2007). A sediment core 7.8 m long was collected from this site and the upper 3.2 m analyzed for plant macrofossils and pollen content (Reasoner and Jodry, 2000). A conifer twig yielded a radiocarbon age of 11,430±70 yr B.P. (CAMS–38704) (about 13,300 cal yr) that was interpreted as indicating that timberline had migrated upslope to near its present elevation during the Bølling-Allerod warming (about 14,600 to 13,000 cal yr). Subsequent declines in arboreal pollen during the Younger Dryas interval (about 12,800 to 11,500 cal yr) suggested a timberline retreat of 60–120 m with a corresponding cooling of summer temperatures by 0.4°–0.9°C (Reasoner and Jodry, 2000). Timberline readvanced to elevations at or above Black Mountain Lake by about 10,000 yr B.P. (about 11,500 cal yr) as indicated by a radiocarbon age of 9,930±70 yr B.P. (CAMS–38702) from an *Abies* needle (Reasoner and Jodry, 2000).

Placer Gulch Bog (3,600 m asl)

The Placer Gulch bog (fig. 2), at an elevation of 3,600 m, is about 2 km downvalley from the head of Placer Gulch. Although no conifers are present near the site, possibly owing to cold-air drainage, krummholz are present on a bedrock ridge about 0.3–0.8 km upvalley from the bog at an elevation of 3,700 m. In addition, several unusually high krummholz live about 0.6 km to the northwest at an elevation of 3,810 m. Timberline is about 1.5 km downvalley at an elevation of 3,560 m; hence, the Placer Gulch bog can be considered to be between present-day timberline and treeline.

An exposure of very dark brown (10YR 2/2 wet) woody peat, 85 cm thick (fig. 14), was found in 1987 next to the tailings pile of the Evening Star mine (fig. 2) (Carrara and others, 1991). The surface at the site and surrounding area had been eroded owing to the mining activity of the late 1800s and early 1900s. Conifer fragments more than 30 cm long and 3 cm in diameter were present throughout the entire section. In addition, several tree stumps about 20–30 cm in diameter appeared to be in growth position. Radiocarbon ages of 6,890±200 yr B.P. (W–6006), 7,020±200 yr B.P. (W–6008), and 8,790±260 yr B.P. (W–6009) were obtained from spruce fragments at depths of 20 cm, 55 cm, and 85 cm, respectively (fig. 8, table 4). The size of the tree stumps suggests that full-sized trees grew at the Placer Gulch site between 8,800 to 6,900 yr B.P. (about 9,800 to 7,700 cal yr), indicating a timberline (and probably a treeline) approximately 40 m higher than at present.

California Gulch Bog (3,615 m asl)

The California Gulch bog, at an elevation of 3,615 m, is about 2 km downvalley from the head of California Gulch (figs. 2, 15). No conifers presently grow near the bog and, in general, the bog is considered to be at present-day treeline although several patches of krummholz about 0.8 km east of the bog on the valley side reach an elevation of about 3,675 m. Timberline is about 1.5 km downvalley near the confluence of California and Placer Gulches at an elevation of 3,585 m.

A pit dug in this bog in 1987 exposed a 155-cm section of very dark brown (10YR 2/2 wet) peat containing four woody peat layers overlying a bedrock surface (fig. 8) (Carrara and others, 1991). Radiocarbon ages were obtained from each of the woody peat layers (fig. 8, table 4). A radiocarbon age of 3,600±50 yr B.P. (USGS–2600) was obtained from willow fragments recovered from the woody peat layer at a depth of 40–50 cm. Radiocarbon ages of 4,330±35 yr B.P. (USGS–2601), 6,850±40 yr B.P. (USGS–2602), and 7,860±40 yr B.P. (USGS–2603) were obtained from spruce fragments recovered from the woody peat layers at 65–75 cm, 105–115 cm, and 140–155 cm depths, respectively.

Spruce fragments within these woody peat layers were usually less than 20 cm long and 3 cm in diameter. However, one fragment from the woody peat layer between 65 and 75 cm was 60 cm long and 10 cm in diameter, and it weighed about 800 g. Because contorted annual growth rings and reaction wood were common in these fragments, they probably were from krummholz growing on the nearby slopes and deposited in the bog by snow avalanches or other mass-wasting processes.

Numerous small coniferous wood fragments, usually less than 3 cm long and 0.5 cm in diameter, were noted in the peat layers between depths of 50 and 65 cm, 75 and 105 cm, and 115 and 140 cm (fig. 8). If one takes into account the overlying radiocarbon age of 3,600±50 yr B.P. (USGS–2600), then the uppermost coniferous wood fragments in the underlying peat are estimated to date from about 3,700 yr B.P. In addition, a small conifer fragment was recovered at a depth of 30 cm. This fragment was too small (0.04 g dry weight) for a conventional radiocarbon age determination, but a sedimentation rate based on the underlying radiocarbon age of 3,600±50 yr B.P. (USGS–2600) suggests an age of about 2,400 yr B.P. for this fragment.

Because the California Gulch bog is considered to be at the present-day treeline, and the wood fragments recovered from the bog were undoubtedly washed into the bog from surrounding higher slopes, the wood fragments indicate a treeline higher than that of present-day from at least as early as 7,900 to 3,700 yr B.P. (about 8,700 to 4,050 cal yr) and possibly for a short time about 2,400 yr B.P. (about 2,450 cal yr).

Bog Near Hurricane Basin (3,660 m asl)

A bog about 1 km from a cirque headwall in the headwaters region of Henson Creek, a tributary of the Gunnison River, is at an elevation of 3,660 m (figs. 16, 17). Although previously referred to as the “Hurricane Basin bog” (Andrews and others, 1975), the bog is actually in a northeast-facing cirque about 1 km northwest of Hurricane Basin. The bog is near present-day treeline, although some krummholz reach an elevation of about 3,700 m on a bedrock ridge 0.6 km northeast of the bog. Only several patches of krummholz are present in the cirque, these being about 100 m north of the bog. Timberline is below the cirque lip about 0.5 km downvalley at an elevation of about 3,600 m.

Much of the evidence that first documented Holocene treeline fluctuations in the northern San Juan Mountains came from this bog. Initial investigations of this bog in 1971 yielded a radiocarbon age of 9,620±440 yr B.P. (St–3909) (about 11,000 cal yr) from organic material concentrated from the basal clay at a depth of 215 cm (Andrews and others, 1975). In 1973 a 210-cm-long core was collected from this bog for radiocarbon dating and pollen and plant macrofossil analysis (Andrews and others, 1975). The core consisted mainly of dark-brown peat that contained three woody peat layers at depths of 70–95 cm, 115–140 cm, and 185–210 cm (Andrews and others, 1975, their table 3) (fig. 8, table 4). A radiocarbon age of 3,520±100 yr B.P. (GaK–3858) was obtained from woody peat at the base of the upper woody layer that contained spruce cone scales and needles. A radiocarbon age of 8,330±75 yr B.P. (SI–1230) was obtained from woody peat near the top of the lower woody layer that also contained spruce macrofossils. Additional radiocarbon ages that provided age control for the pollen diagram were 280±80 yr B.P. (GaK–3859), obtained from a wood fragment at a depth of 10 cm, and 1,295±70 yr B.P. (SI–1231), obtained from peat at a depth of 55 cm (Andrews and others, 1975) (fig. 8). No spruce macrofossils were noted above the horizon dated at 3,520±100 yr B.P., whereas spruce macrofossils were noted below the horizon dated at 8,330±75 yr B.P. (Andrews and others, 1975) (fig. 18). The base of the core was thought to date from about 9,000 yr B.P.

Figure 14. Placer Gulch bog study site; exposure is near Evening Star Mine.

Analysis of the Hurricane Basin core indicated that before about 8,500 yr B.P., percentages of spruce, pine, and total arboreal pollen were relatively low, whereas percentages of sagebrush pollen were relatively high (Andrews and others, 1975, their fig. 7). In addition, spruce/pine pollen ratios were low (Andrews and others, 1975) (fig. 18). These data seemingly indicate a cooler climate with a lower than present-day timberline; however, the presence of spruce macrofossils indicates that spruce was growing near this bog and suggests that even at this time timberline was probably higher than at present.

Between about 8,500 and 3,500 yr B.P. (about 9,500 and 3,775 cal yr) spruce pollen is relatively abundant (>12 percent), as is total arboreal pollen, and spruce/pine pollen ratios are generally higher than at present. In addition, during this period spruce macrofossils are common in the core (Andrews and others, 1975) (fig. 18). A drop in spruce/pine ratios about 7,600 yr B.P. (about 8,400 cal yr) seems to have been caused by an abnormally large amount of pine pollen in the section at this time and is not thought to represent a climatic event, because the percentage of spruce pollen remained fairly high. These data indicate that spruce was closer to the bog (hence the climate was warmer than at present) during this period. After about 3,500 yr B.P., spruce pollen and spruce/pine pollen ratios decrease, and in addition, no spruce macrofossils were identified after this time. These data suggest a lower timberline and hence cooler climate after 3,500 yr B.P. (about 3,775 cal yr).

This bog was revisited in 1986 and a 215-cm-deep pit was dug to the underlying bedrock surface (Carrara and others, 1991). The pit exposed dark yellowish-brown (10YR 4/6 wet) peat that contained three woody peat layers at depths of 70–90 cm, 140–150 cm, and 190–205 cm (fig. 8). The woody peat layer between 140 and 150 cm contained numerous spruce fragments. Conifer fragments in this layer were generally small and platy, usually less than 3–5 cm in length and width and 1 cm thick. These fragments yielded a radiocarbon age of 5,630±250 yr B.P. (W–5867) (fig. 8, table 4). In addition, Carrara and others (1991) obtained a radiocarbon age of 8,420±250 yr B.P. (W–5866) from willow fragments from the lower woody peat layer from which spruce macrofossils were identified (fig. 8, table 4).

Together the Hurricane Basin data may be interpreted as indicating that treeline was at least slightly higher than at present from about 9,000 to 3,500 yr B.P. (about 10,150 to 3,770 cal yr). After 3,500 yr B.P. (about 3,770 cal yr) treeline was lower than at present and rose to its present elevation only in the last several hundred years (Andrews and others, 1975) (fig. 18).

Table 4. Radiocarbon ages from bogs in the northern San Juan Mountains, Colo.

[cal yr, calendar years before present; m, meters; yr B.P., radiocarbon years before present]

Bog (altitude)	Material dated	Depth (m)	Laboratory number	^{14}C age (yr B.P.)	Calendar year (cal yr)[a]
Placer Gulch (3,600 m)	Spruce fragments	20	W–6006	6890±200	7731±179
	Spruce fragments	55	W–6008	7020±200	7849±188
	Spruce fragments	85	W–6009	8790±260	9848±345
California Gulch (3,615 m)	Willow fragments	40–50	USGS–2600	3600±50	3903±66
	Spruce fragments	65–75	USGS–2601	4330±35	4872±35
	Spruce fragments	105–115	USGS–2602	6850±40	7675±31
	Spruce fragments	140–155	USGS–2603	7860±40	8629±50
Near Hurricane Basin (3,660 m)	Willow fragment	10	GaK–3859	280±80[b]	Out of calibration range
	Peat	55	SI–1231	1295±70[b]	1229±72
	Woody peat[c]	90–95	GaK–3858	3520±100[b]	3799±132
	Spruce fragments	140–150	W–5867	5630±250	6424±273
	Woody peat	190–195	SI–1230	8330±75[b]	9347±105
	Willow fragments[d]	190–205	W–5866	8420±250	9404±293
	Organic material in basal clay	210	SI–1232	8455±85[b]	9468±66
	Organic material in basal clay	215	St–3909	9620±440[b]	10,986±647
Eureka Gulch (3,665 m)	Organic silty clay[e]	105–130	USGS–2466	3905±40	4353±67
	Conifer fragments	170–180	USGS–2716	6180±160	7069±199
	Spruce fragments	200–205	USGS–2467	8320±70	9335±103
	Willow fragments	235–240	USGS–2468	9260±60	10,440±97
Picayne Gulch (3,750 m)	Willow fragments[f]	95–105	W–5863	6000±300	6846±349
	Willow fragments	120–130	W–6013	8350±250	9323±300

[a]Data accessed on the World Wide Web at *http://www.radiocarbon.LDEO.columbia.edu* on March 20, 2009. See Fairbanks, R.G. and others, 2005, Marine radiocarbon calibration curve spanning 0 to 50,000 years B.P., based on paired $^{230}Th/^{234}U/^{238}U$ and ^{14}C dates on pristine corals: Quaternary Science Reviews, v. 24, p. 1781–1796.

[b]Radiocarbon age from Andrews and others (1975); depth represents a combined stratigraphy of Andrews and others (1975) and Carrara and others (1991).

[c]Woody peat containing spruce macrofossils (Andrews and others, 1975).

[d]From same woody peat layer in which Andrews and others (1975) identified spruce macrofossils.

[e]Contained two conifer fragments too small for a conventional radiocarbon age determination.

[f]Woody layer contained mainly willow fragments, but two small spruce fragments were also recovered from this layer.

Figure 15. California Gulch looking upvalley; bog study site is in foreground.

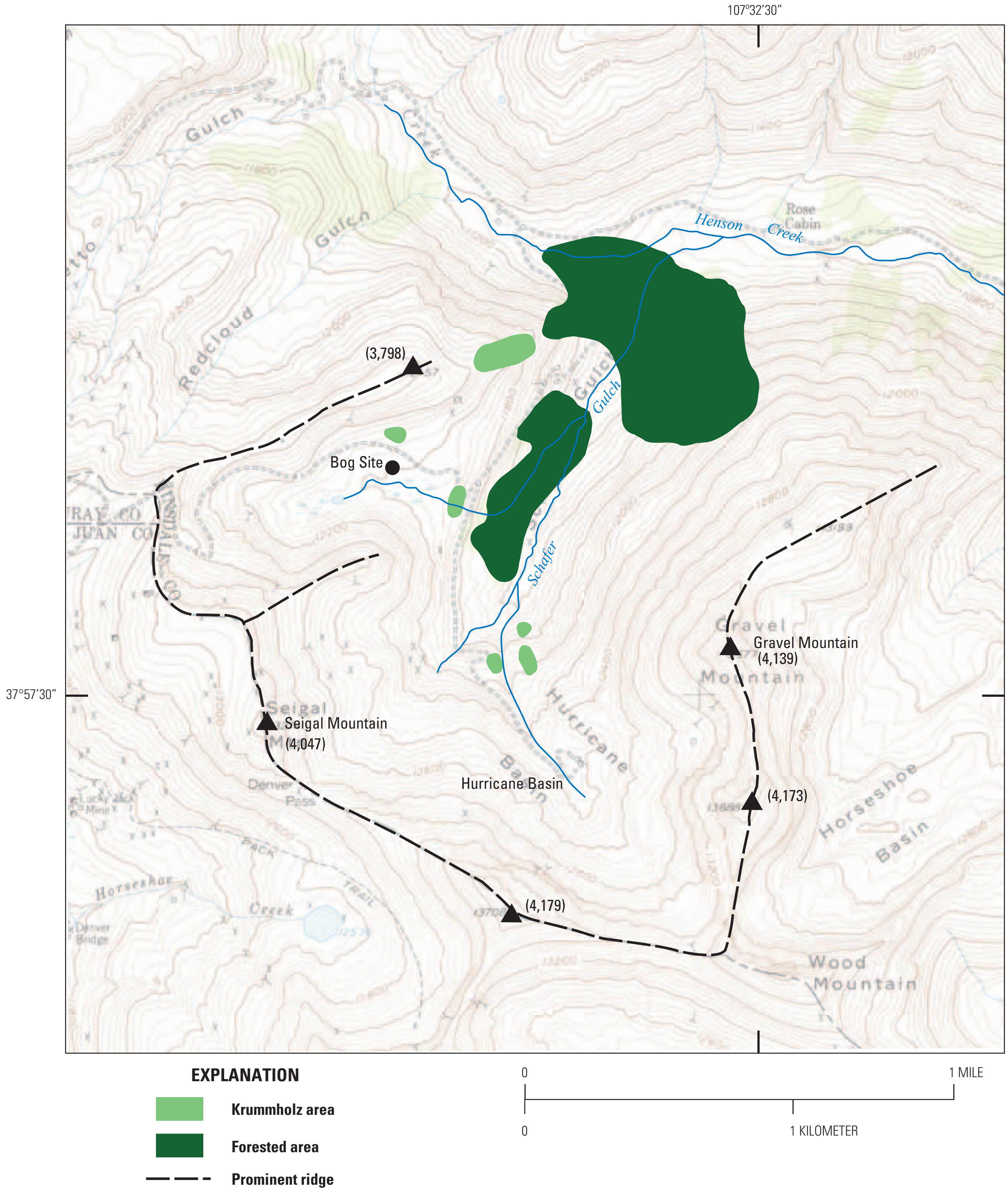


Figure 16. Hurricane Basin area. Elevations are in meters.

Figure 17. Bog near Hurricane Basin; bog was originally visited in 1971 and again in 1973 and 1986. S.P. Schilling augering through the sediments to determine sediment thickness and presence of woody peat layers.

Eureka Gulch Bog (3,665 m asl)

The Eureka Gulch bog, at an elevation of 3,665 m, is near the head of Eureka Gulch, about 0.8 km south of the Lake Emma site (figs. 2, 19). The bog lies near treeline, and the nearest krummholz are a small patch of subalpine fir at the base of a south-facing cliff about 200 m west of the bog. Timberline is about 1 km downvalley at an elevation of 3,600 m.

A pit was dug in the Eureka Gulch bog in 1972 and radiocarbon ages of 740±70 (SI–1238), 3,150±135 (SI–1239), and 5,665±60 (SI–1240), were obtained from peat and organic silt layers at depths of 45 cm, 115 cm, and 145 cm respectively (Andrews and others, 1975, their table 2). In addition, a radiocarbon age of 8,785±45 yr B.P. (SI–1241) was obtained from a woody peat at a depth of 215–220 cm at the base of the pit. Unfortunately, it is not known if this wood was coniferous, and hence its relation to treeline fluctuations is not clear.

The Eureka Gulch bog was revisited in 1986 and 1987, and a new pit was dug near the site of the 1972 pit that exposed a 245-cm section overlying a bedrock surface (Carrara and others, 1991). This section contained layers of dark yellowish-brown (10YR 3/4 wet) peat and dark-gray (10YR 4/1 wet) to very dark grayish-brown (10YR 3/2 wet) organic silty clays that overlay a greenish-gray (5G 6/1 wet), inorganic sandy clay (fig. 8).

Four radiocarbon ages were obtained from the Eureka Gulch bog (fig. 8, table 4) (Carrara and others, 1991). The uppermost coniferous macrofossils consisted of two small wood fragments at depths of 110 and 120 cm. Because these conifer fragments were too small (0.2 g dry weight) for conventional radiocarbon dating, a radiocarbon age of 3,905±40 yr B.P. (USGS–2466) was obtained from the organic silty clay between depths of 105 and 130 cm from which these conifer fragments were recovered. In addition, a radiocarbon age of 6,180±160 yr B.P. (USGS–2716) was obtained from several small (1.6 g dry weight) conifer wood fragments at a depth of 170–180 cm at the base of a peat (fig. 8).

Numerous small wood fragments were found in an organic silty clay unit between depths of 200 and 240 cm (Carrara and others, 1991). Most of these wood fragments were less than 2 cm long. A radiocarbon age of 8,320±70 yr B.P. (USGS–2467) was obtained from spruce fragments collected between depths of 200 and 205 cm. All wood fragments recovered below this depth were identified as willow. A radiocarbon

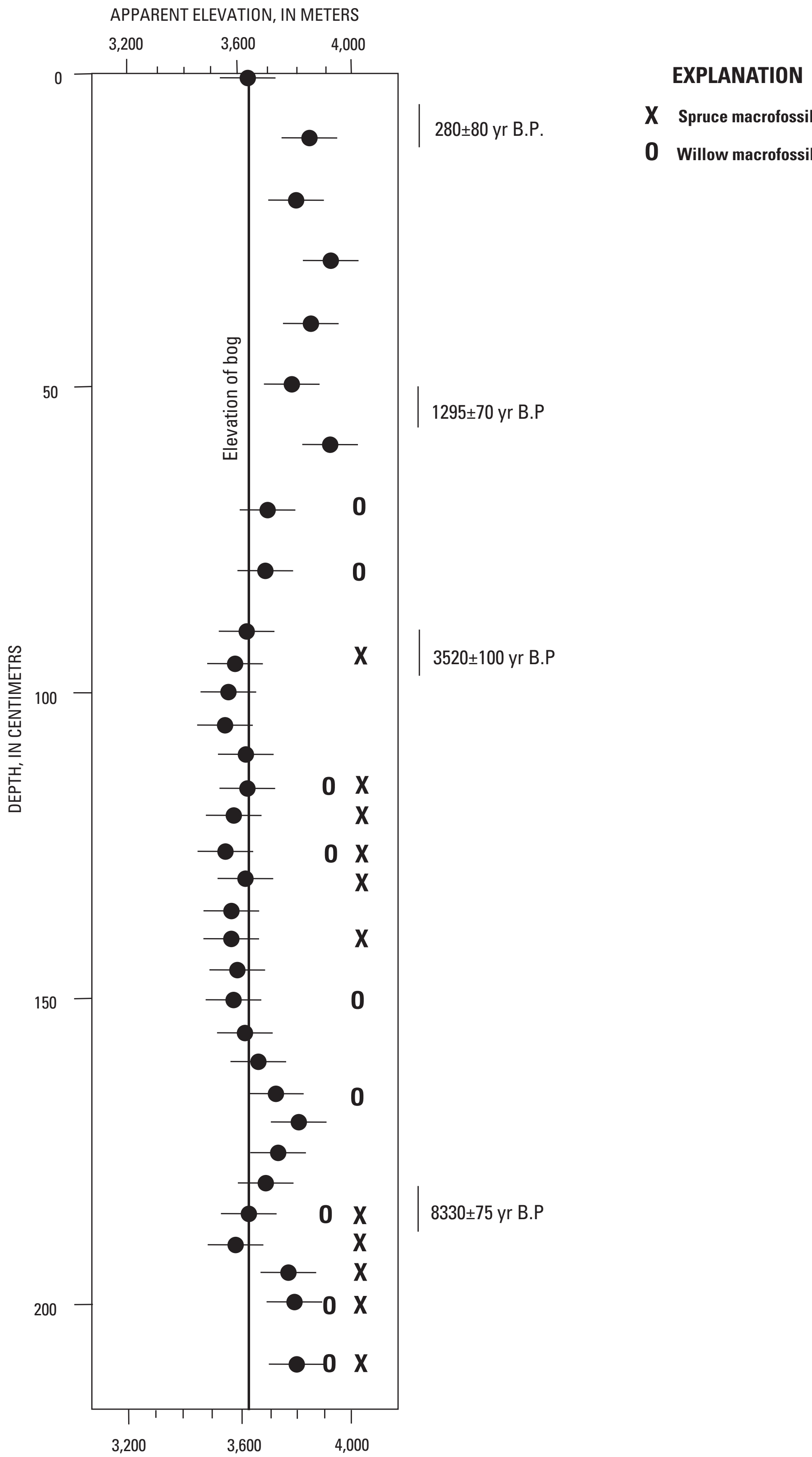


Figure 18. Changing apparent elevation of the Hurricane Basin core based on spruce/pine ratios; radiocarbon ages (yr. B.P.) and location of macrofossils also shown (after Andrews and others, 1975).

Figure 19. Eureka Gulch bog, about 0.8 km south of Lake Emma; study site in foreground.

age of 9,260±60 yr B.P. (USGS–2468) was obtained from willow fragments collected between depths of 235 and 240 cm (fig. 8, table 4).

The radiocarbon ages of the conifer fragments from the Eureka Gulch bog indicate a treeline at least as high as at present about 8,300 yr B.P. (about 9,300 cal yr) and 6,200 yr B.P. (about 7,100 cal yr), and possibly about 3,900 yr B.P. (about 4,350 cal yr). From the sparse evidence at this site, nothing definitive can be determined about the position of treeline between these three dates.

Lake Emma Site (3,740 m asl)

The Lake Emma site, at an elevation of 3,740 m in a south-facing cirque, is at the head of Eureka Gulch near the headwaters of the Animas River (figs. 1, 2). The cirque has been the site of extensive gold and silver mining since 1874, when the San Juan Mountains were opened to settlement (Bird, 1986) (fig. 20). Lake Emma had a surface area of about 0.05 km^2 and a maximum depth of about 5 m; its outlet was across a bedrock lip at its southern end. On 4 June 1978, it was suddenly and completely drained by the collapse of underground mine workings (fig. 4) (Carrara and Mode, 1979; Marcus and Marcus, 1983; Carrara and others, 1984, 1991). This unfortunate event had beneficial consequences for paleoclimate studies because the lake's sediments were incised by the escaping waters, which exposed a well-preserved archive of subfossil wood above present-day treeline.

Radiocarbon-Dated Conifer Fragments

Numerous spruce and fir wood fragments were found scattered among the deposits of Lake Emma (Marcus and Marcus, 1983; Carrara and others, 1984, 1991). Most of these fragments were small, usually less than 20 cm long, 5 cm in diameter, and 500 g (dry weight). That these wood fragments are probably from krummholz is indicated by the

1. Small size of the fragments,
2. Contorted patterns of the annual rings (fig. 21), and
3. Presence of reaction wood commonly found in trees above timberline (Tranquillini, 1979).

However, one spruce fragment recovered from the sediment of Lake Emma, which was 70 cm long, 30 cm in diameter, and more than 5 kilograms (kg) (dry weight), yielded a radiocarbon age of 8,010±80 yr B.P. (Lk Emma 18–81) (table 2). This fragment contained about 150 annual rings that displayed a complacent growth record and, hence, appeared to have come from a large, upright tree.

Krummholz do not presently grow in the Lake Emma cirque, which is occupied solely by alpine tundra vegetation

Figure 20. Lake Emma and the adjacent Sunnyside Mine, about 1900 AD. Photograph courtesy of the San Juan County, Colo., Historical Society.

Figure 21. Cross section of a spruce fragment from the Lake Emma site that yielded radiocarbon ages of 3,120±80 yr B.P. (W–4242) and 3,075±35 yr B.P. (USGS–2617) (see also table 2). Contorted pattern of annual rings and the presence of reaction wood suggest that the fragment was from krummholz.

(fig. 4). Treeline in Eureka Gulch is about 0.9 km downvalley from the Lake Emma site at an elevation of 3,660 m, although a few krummholz attain an elevation of about 3,700 m on the northeast shoulder of Emery Peak about 1.25 km to the south-southeast (fig. 2). Timberline is about 1.5 km downvalley at an elevation of 3,600 m.

No evidence was found to suggest that the krummholz limit (treeline) was altered by mining activity at Lake Emma during the 19th or 20th century. It is doubtful that early miners would have removed krummholz from the Lake Emma cirque, because it is not suitable for mine timbers and does not appear to have been removed elsewhere in the San Juan Mountains. Krummholz is not present on photographs of Lake Emma and the Sunnyside Mine taken about 1900 AD (fig. 20). A miner employed at the Sunnyside Mine during the 1920s does not recall any trees in the Lake Emma cirque (Eric Hoffman, oral commun., 1979). At lower elevations where full-sized trees were logged for mining operations, stumps are numerous and well preserved; no stumps are present in the Lake Emma cirque. Furthermore, allowing for differences caused by aspect, snow avalanches, and cold-air drainage, the elevation of treeline is similar in valleys in the northern San Juan Mountains regardless of the degree of past mining activity.

It is unlikely that these conifer fragments were blown upvalley to the Lake Emma site. Oven-dry weights of these fragments were generally more than 25 g and as much as 5 kg. These fragments were from trees, probably krummholz (except for the fragment discussed above, Lk Emma 18–81; table 2) growing on the surrounding slopes and deposited in Lake Emma by snow avalanches or other mass-wasting processes.

Coniferous wood fragments were collected during visits to the Lake Emma site between 1978 and 1987. Each year, further erosion of the lake deposits revealed additional wood fragments that were collected for identification and radiocarbon dating. In any given year fragments were collected several meters from one another to reduce the probability of dating more than one fragment from the same tree. All wood fragments were collected from surface exposures of Lake Emma deposits, with 5 exceptions: 3 conifer fragments (LE Pollen (81)−79, (96) −79, and (161)−79; table 2) that were collected from a section sampled for pollen analysis in 1979 (Carrara and others, 1984); and 1 conifer fragment (LE Fos Insect 02–87) (table 2), and 1 willow fragment (9,400±70 yr B.P. (AA–3888)) that was collected from a nearby section in 1987 for fossil insect analysis (Elias and others, 1991) (fig. 7).

Sixty-six radiocarbon ages were obtained from 53 coniferous wood fragments from the Lake Emma site (table 2). Carrara and others (1991) presented 41 of these radiocarbon ages, 39 of which formed an almost continuous suite of radiocarbon ages from about 9,600 to 5,400 yr B.P. (about 10,950 to 6,200 cal yr). In addition, two radiocarbon ages from the same spruce fragment (Stand Metals 01–78, table 2) gave ages of about 3,100 yr B.P. (about 3,300 cal yr) (fig. 21). The number of annual rings in 52 of the 53 dated conifer fragments ranged from 4 to 100 (average about 40). The pith was present in most of the samples submitted for radiocarbon dating. Hence, the age range of the wood in each fragment was in most cases smaller than the error limit of the radiocarbon age. Because one sample (Lk Emma 18–81; table 2) contained about 150 annual rings, the wood submitted for dating from this sample was taken from the pith region.

Of the 53 coniferous fragments submitted for radiocarbon dating, 47 (89 percent) were spruce and 6 (11 percent) were fir (table 2). Of the 35 krummholz trees inspected on the northeast flank of Emery Peak (fig. 2), 32 (91 percent) were spruce and 3 (9 percent) were fir. Hence, the present-day dominance of Engelmann spruce as compared with subalpine fir among krummholz is mirrored by the radiocarbon-dated fossil samples.

Many of the coniferous wood samples from Lake Emma no longer exist, because they were completely consumed by either radiocarbon dating (Carrara and others 1984, 1991; Elias and others, 1991) or deuterium analyses (Friedman and others, 1988; Epstein and others, 1999). These consumed samples include two of the oldest samples (9580±130 yr B.P. (USGS–1341), and 9220±120 yr B.P. (W–4524)). To confirm the reliability of earlier age determinations, some older remaining wood fragments originally dated by conventional radiocarbon methods were subsequently dated by AMS. One sample (Lk Emma 16–80) originally dated at 9,520±90 yr B.P. (USGS–1345) yielded an AMS radiocarbon age of 8,656±50 yr B.P. (WW–5548) (table 2). Another sample (Lk Emma 05–83), originally dated at 9,000±300 yr B.P. (W–5611) yielded an AMS age of 8,855±51 yr B.P. (WW–5547). Although the error limit of these two radiocarbon ages overlap, indicating that they may be the same, the AMS age produced a substantially younger age with a much smaller error limit and is thus considered the more accurate of the two. A third sample (Lk Emma 01–87) originally dated at 8,950±45 yr B.P. (USGS–3181) yielded an AMS radiocarbon age of 7820±30 (WW–6592). Three additional samples (Lk Emma 06–79, Lk Emma 14–79, and Lk Emma 05–85), which initially yielded conventional radiocarbon ages between about 8,820 and 8,730 yr B.P., subsequently yielded similar AMS ages (table 2). Hence, subsequent AMS radiocarbon dating cannot confirm that any of the coniferous wood fragments recovered from the Lake Emma site are older than 9,000 yr B.P. (about 10,150 cal yr).

However, the radiocarbon age from the spruce fragment (LE Pollen (161)–79), which yielded a conventional radiocarbon age of 9,220±120 yr B.P. (W–4524), appears to be accurate. As mentioned above, this sample was consumed in prior radiocarbon dating and deuterium analyses, so it cannot be dated again. However, the sample was recovered from a stratigraphic section sampled for pollen analysis in 1979 (Carrara and others, 1984). In 1987 two small wood fragments were recovered from a nearby section (about 2 m away) sampled for insect analysis (Elias and others, 1991). An AMS radiocarbon age of 9,400±70 yr B.P. (AA–3888) was obtained from a willow fragment at the same the horizon as this spruce fragment (fig. 7) (Elias and others, 1991, their table 2). In addition, another spruce fragment recovered approximately 15 cm above these two wood fragments yielded an AMS radiocarbon age of 8,625±90 yr B.P. (AA–3889) (Elias and others, 1991, their table 2). Hence, it appears that spruce was indeed growing around the Lake Emma site (above present-day treeline) by 9,200 yr B.P. (about 10,400 cal yr).

Again, to confirm the reliability of earlier age determinations, some younger remaining wood fragments from the Lake Emma site originally dated by conventional radiocarbon methods were subsequently dated by AMS. One sample (Lk Emma 04–86), originally dated at 5,370±110 yr B.P. (USGS–3005), yielded an AMS radiocarbon age of 5,858±40 yr B.P. (WW–6115) (table 2). A second sample (Lk Emma 09–83), originally dated at 5,420±200 yr B.P. (W–5616), yielded an AMS radiocarbon age of 5,870±30 yr B.P. (WW–6593). Finally, a third sample (Lk Emma 04–79), originally dated at 5,570±70 yr B.P. (W–4680), yielded an AMS age of 5,839±40 yr B.P. (WW–6118). An additional small wood fragment (LE Pollen (81)–79) originally collected in 1979 yielded a conventional radiocarbon age of 5,440±100 yr B.P. (USGS–2135) (fig. 7). Although this age fits reasonably well with the other radiocarbon ages from wood fragments in the stratigraphic section (fig. 7), because this fragment was completely expended in the process of radiocarbon dating, subsequent AMS dating cannot verify its age. Hence, except for the spruce fragment (Stand Metals 01–78) dated by conventional radiocarbon methods at about 3,100 yr B.P. (about 3,300 cal yr) by two different labs (table 2), subsequent AMS radiocarbon dating cannot confirm that any of the coniferous wood fragments recovered from the Lake Emma site are younger than about 5,800 yr B.P. (about 6,600 cal yr).

From the above discussion and the radiocarbon ages listed in table 2, it can be concluded that treeline at the Lake Emma site was at least 80 m higher than at present from about 9,200 to 5,800 yr B.P. (about 10,400 to 6,600 cal yr). Treeline may have remained at this higher elevation until about 5,400 yr B.P. (about 6,200 cal yr), and possibly returned for a brief period about 3,100 yr B.P. (about 3,300 cal yr). In addition, the radiocarbon age of 8,010±80 yr B.P. (USGS–1346) of a large conifer fragment (Lk Emma 18–81) from a full-sized tree indicates timberline was at least 140 m higher than at present about 8,000 yr B.P. (about 8,900 cal yr).

Pollen Analysis

In addition to the radiocarbon age determinations of the coniferous fragments at Lake Emma, a section of exposed sediment was sampled for pollen analysis in 1979 (Carrara and others, 1984; their fig. 3) and a nearby section (2 m away) was sampled in 1987 for fossil insect analysis (Elias and others, 1991); the combined stratigraphic section is presented in figure 7. Because the upper 29 cm of the section was disrupted by the sudden draining of the lake, no samples were taken from that part of the section. In addition, because the uppermost sediments were eroded during the drainage of the lake, a surface sample was collected from a nearby locality where sediments appeared undisturbed.

Radiocarbon ages were originally determined from organic material taken from three horizons (Carrara and others, 1984, their fig. 3). Spruce fragments at depths of 96 and 161 cm yielded radiocarbon ages of 6,670±70 yr B.P. (W–4523) and 9,220±120 yr B.P. (W–4524), respectively (fig. 7). Detrital terrestrial moss in the basal 10 cm of the organic-rich laminated sediments yielded radiocarbon ages of 14,900±250 yr B.P. (W–4209), 14,130±150 yr B.P. (W–4289), and 14,940±140 yr B.P. (W–4525) (fig. 7). These radiocarbon ages are now thought to be too old; see the following discussion.

An age of the uppermost sediment sampled at Lake Emma for pollen analysis was originally estimated on the basis of sedimentation rates (Carrara and others, 1984). By using the radiocarbon ages of the two spruce fragments at depths of 96 and 161 cm (see above), a sedimentation rate of 0.025 centimeters per year (cm/yr) was calculated. Extrapolation of this rate yielded an estimated age of about 4,000 yr B.P. for the uppermost sediment sampled (at 31 cm depth). A subsequent radiocarbon age of 5,440±100 yr B.P. (USGS–2135) was obtained from a conifer fragment (LE Pollen (81)–79) at a depth of 81 cm (fig. 7). A new sedimentation rate (0.012 cm/yr) determined between the radiocarbon ages of 6,670±70 (age of the spruce fragment at 96 cm depth) and 5,440±100 yr B.P. (LE Pollen (81)–79) was extrapolated and yielded an estimated age of about 1,300 yr B.P. for the upper pollen sample at a depth of 31 cm. However, because of the problems of extrapolation, this estimated age of 1,300 yr B.P. must be viewed with caution, and it is best to interpret the pollen data only to the 5,440 yr B.P. date.

The age of the basal sediment in Lake Emma has also been revised from the original ages given by Carrara and others (1984) (Elias and others, 1991). The radiocarbon ages of the detrital moss fragments are now thought to be as much as 6,000 radiocarbon years too old (fig. 7) (Elias and others, 1991). A radiocarbon age of 12,900±200 yr B.P. (W–5972) was obtained from detrital moss fragments at a depth of 170–180 cm. Willow fragments from this same depth yielded a radiocarbon age of 9,400±70 yr B.P. (AA–3888) (Elias and others, 1991, their table 2). Furthermore, the spruce fragment originally collected in 1979 that yielded a radiocarbon age of 9,220±120 yr B.P. (W–4524) is also from this same horizon (fig. 7). A radiocarbon age of 13,580±200 yr B.P. (W–5974) was obtained from detrital moss fragments at a depth of 195–205 cm, whereas insect remains from this same depth yielded a radiocarbon age of 8,200±160 yr B.P. (AA–4826). Finally, as previously mentioned, radiocarbon ages of 14,000–15,000 yr B.P. were obtained from detrital moss fragments from the lowermost 10 cm of sediments from Lake Emma that also contained several spruce needles. Insect remains from this same sediment yielded radiocarbon ages of 8,940±85 yr B.P. (AA–4824) and 9,020±80 yr B.P. (AA–4825) (fig. 7) (Elias and others, 1991, their table 2).

Hence at Lake Emma, radiocarbon ages of wood fragments are about 3,600 years younger than radiocarbon ages of detrital moss fragments from the same horizon (fig. 7). Radiocarbon ages of insect remains range from about 5,000 to 6,000 years younger than radiocarbon ages of detrital moss fragments from the same horizon. Although radiocarbon ages were not obtained from wood fragments and insect remains from the same horizon, inspection of figure 7 shows that radiocarbon ages of insect remains are at least 1,000 years younger than those of the wood fragments.

Reasons for the differences in radiocarbon ages from different material from the Lake Emma site are not known (Elias and others, 1991). As previously mentioned, the moss fragments were determined to be from a terrestrial moss (J.A. Janssens, written commun., 1982). Hence, the radiocarbon ages obtained from the moss fragments from Lake Emma were thought to be free of any hard-water effect. Terrestrial mosses assimilate only atmospheric carbon, whereas aquatic mosses are known to assimilate carbon from water and hence may be subject to a "hard water" effect (MacDonald and others, 1987). Even if the moss fragments were from aquatic mosses, it is doubtful that Lake Emma was a hard-water lake. Although minor amounts of carbonate minerals (calcite and rhodochrosite) are associated with the local mineralization, the bedrock in the Lake Emma cirque is volcanic and contains no carbonate. Discussions with several experts in the field of radiocarbon dating and bryophyte biology have failed to provide any insights into this problem (Minze Stuiver, oral commun., 1980; Meyer Rubin, oral commun., 1989; T.W. Stafford, oral commun., 1990; P.H. Glaser, oral commun., 1988). Hence, the reason for the spurious radiocarbon ages of the mosses remains unexplained. Nevertheless, it is apparent that the age of deglaciation of the San Juan Mountains must be revised.

The age of the base of the exposed sediment section sampled at Lake Emma is problematic. Clearly, the moss ages are too old. However, radiocarbon ages of the wood fragments suggest an age of about 10,000 yr B.P. (about 11,500 cal yr) or greater, whereas the radiocarbon ages of the insect remains suggest an age of about 9,000 yr B.P. (about 10,150 cal yr). Reasons for the differences in radiocarbon ages between the wood fragments and the insect remains are not known (Elias and others, 1991).

The pollen-percentage diagram from Lake Emma is dominated by *Picea*, *Pinus*, *Artemisia*, and *Poaceae* (Carrara and others, 1984) (fig. 22). The *Picea* curve is relatively uniform throughout the entire section; values range between 4 percent (at 46 cm depth) and 12 percent (at 91 cm depth) and average about 8 percent. The surface sample contains 6 percent *Picea*. The *Pinus* curve has two sections, a lower one (below 131 cm depth, about 8,000 yr B.P.) that averages about 40 percent and an upper section that averages about 25 percent. The surface sample contains 25 percent *Pinus*. The *Artemisia* curve can also be divided into two sections, a lower section (below 171 cm depth, about 9,450 yr B.P.) that averages about 27 percent and an upper section that averages about 20 percent. In the surface sample *Artemisia* is 23 percent. The *Poaceae* curve indicates an overall increase from the bottom to the top of the section. Below 151 cm depth (about 8,850 yr B.P.), *Poaceae* percentages are low and average only 10 percent; above this depth percentages increase and average about 19 percent; they reach 30 percent in the upper pollen sample. The surface sample contains 15 percent *Poacea*.

The pollen-concentration summary diagram (Carrara and others, 1984) (fig. 23) shows high and increasing concentrations of most pollen types between the base of the section and 138 cm depth (about 8,300 yr B.P.). Above 138 cm, pollen concentration drops sharply. This drop in pollen concentration is especially marked for *Pinus* and *Artemisia*.

The decline in pollen concentration above 138 cm may have been caused by nonclimatic factors. Although sediment size data revealed no significant changes, an increase in sedimentation rate could account for a decrease in pollen concentration. Additionally, Lake Emma may not have existed immediately upon deglaciation. The bedrock that underlies the Lake Emma basin is cut by numerous faults and fractures, and miners working in the large stope under the lake had long complained of leakage (Eric Hoffman, oral commun., 1979). After deglaciation, leakage may have delayed the establishment of Lake Emma. This interpretation is supported by the fact that the basal sediment consisted of terrestrial moss fragments rather than fine-grained lacustrine sediment (Carrara and others, 1984). Hence, the decrease in pollen concentration may simply reflect the sealing of the basin by sediment and establishment of Lake Emma. An outlet stream of the newly formed lake may have flushed some of the pollen rain from the basin.

The section of exposed sediments sampled for pollen analysis at Lake Emma contained three spruce fragments that were radiocarbon dated (LE Pollen (81)–79, (96)–79, and (161)–79) (table 2). In addition, because the percentage of spruce pollen in the pollen-percentage diagram (fig. 22) is relatively uniform throughout the section and, as previously mentioned, the lowermost 10 cm of sediments contained several spruce needles, it can be argued that spruce was growing near Lake Emma continuously during the time represented by the section—from about 10,000 to 5,800 yr B.P. (about 11,500 to 6,600 cal yr) and maybe as late as 5,400 yr B.P. (about 6,200 cal yr). As discussed above, the radiocarbon ages of coniferous wood fragments from this site clearly indicate the presence of conifers (and a higher than present-day treeline) about 9,200–5,800 yr B.P. (about 10,400–6,600 cal yr).

Fossil Insects

A higher than present-day treeline during the early Holocene is also supported by analysis of fossil insects from the basal sediments of Lake Emma (Elias, 1982; Elias and others, 1991). Sampling for fossil insects at the Lake Emma site began in 1979 (Elias, 1982) when about 20 kg of organic-rich sediment was collected from the lower 10 cm of the basal organic unit. At that time, about 8 kg of modern lake sediment

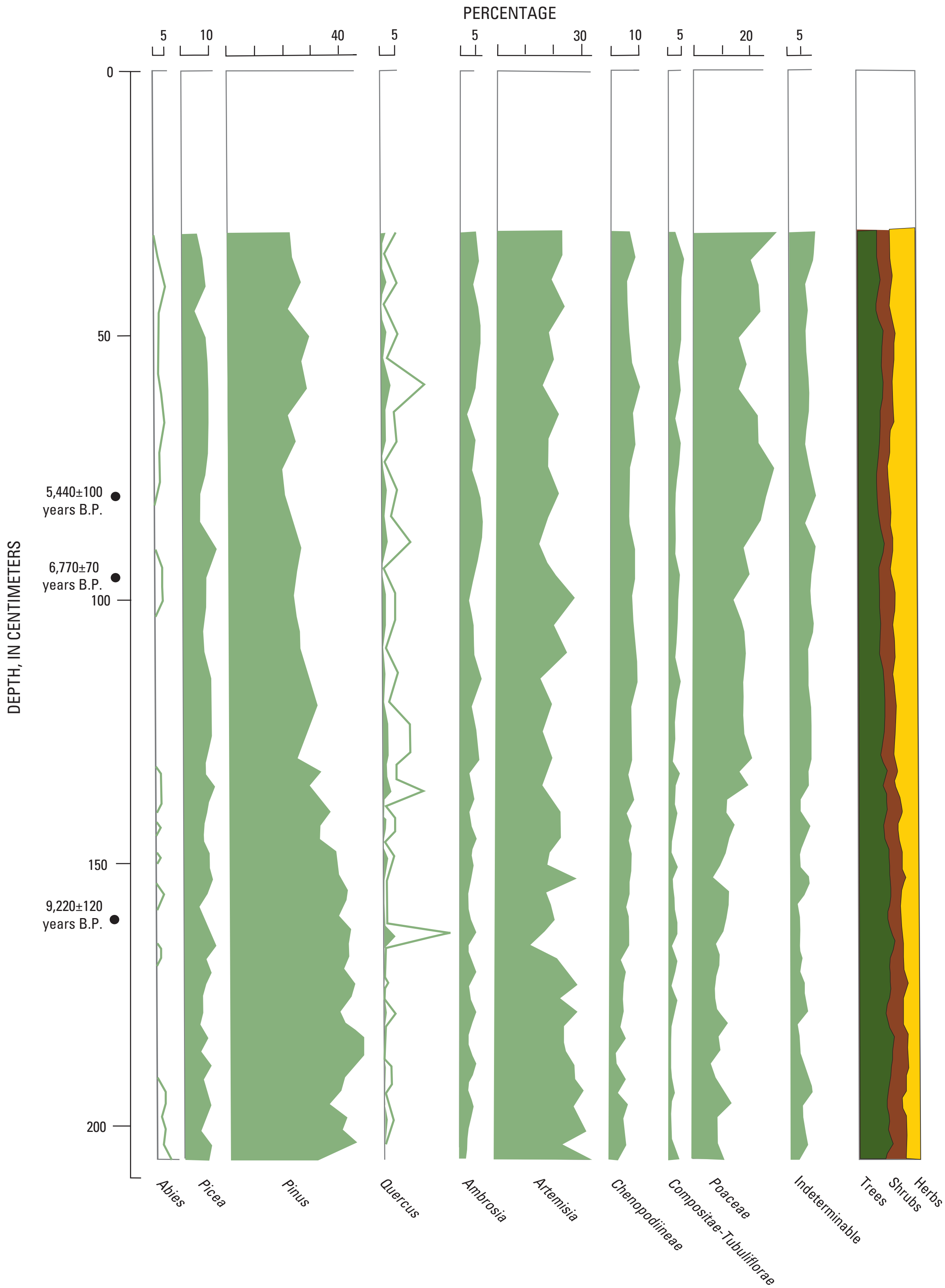


Figure 22. Pollen percentage summary diagram from Lake Emma. Solid line for *Abies* and *Quercus* represents 5× exaggeration (after Carrara and others, 1984). B.P., before present.

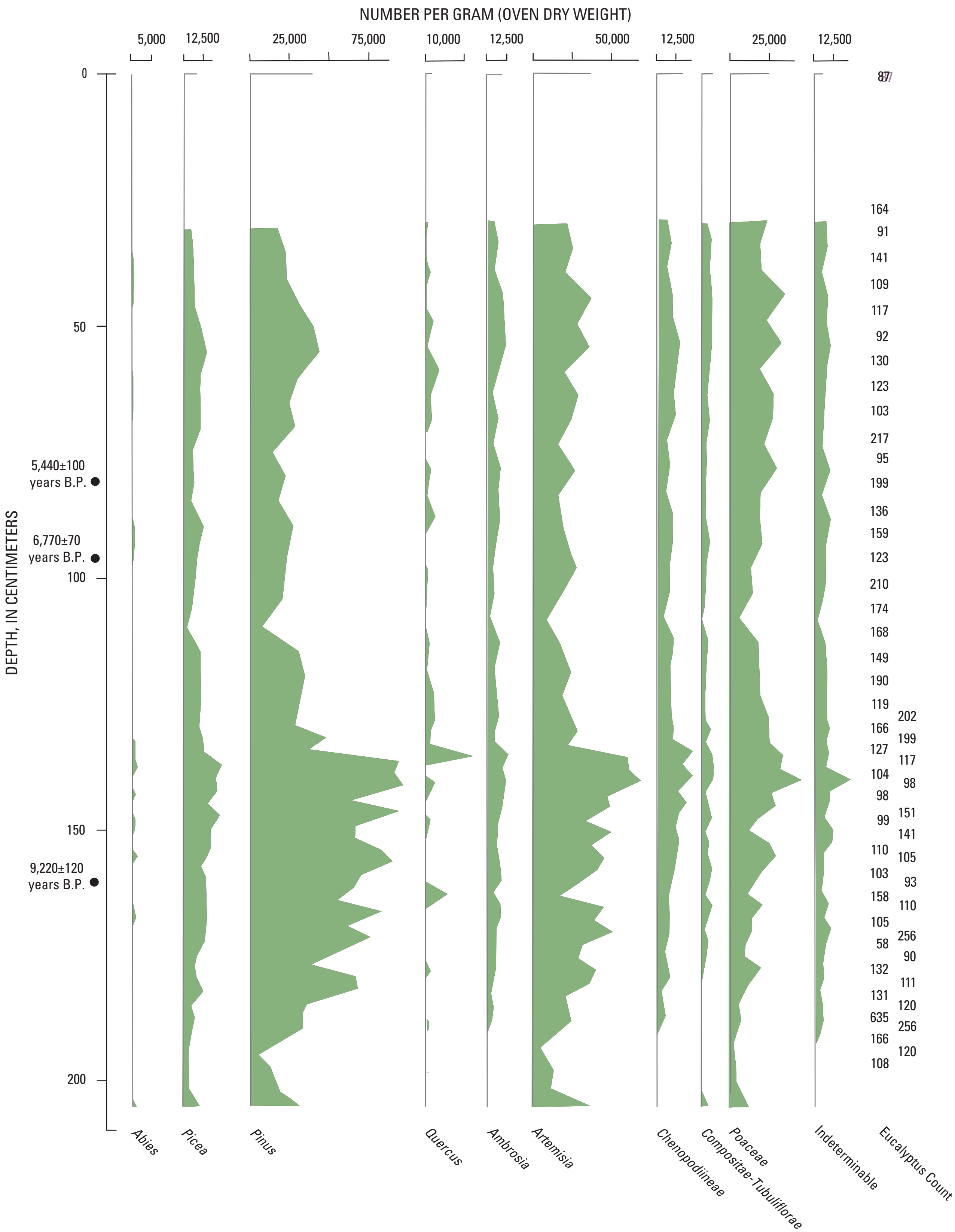


Figure 23. Pollen concentration summary diagram from Lake Emma (after Carrara and others, 1984). B.P., before present.

was also collected for comparison with present-day insects. In 1987, samples were taken from three horizons in the basal organic unit (fig. 7); each sample weighed about 15 kg (Elias and others, 1991). In addition, modern insects were collected in the vicinity of the former Lake Emma.

The sediment samples from the three horizons in the basal organic unit yielded remains of a minimum of 185 insects that represented 44 taxa, in 18 families, from 5 insect orders (Elias and others, 1991). The samples show a surprising diversity of species (19 were identified), given the small number of individuals recovered. Because no differences in the environmental conditions are implied by the fossil insects from the three horizons, information from the horizons was combined (Elias and others, 1991). The fossil insect assemblages contain a high proportion (31 percent) of bark beetles. This assemblage contrasts sharply with the insect remains in the modern lake sediment and with those insects collected live; only one bark beetle was recovered. In addition, the fossil assemblages contained a number of flightless insect species not subject to wind transport and indicative of coniferous forests, whereas tundra-related fossil insects were absent (Elias and others, 1991). The insect fossils from the basal organic sediments of Lake Emma were interpreted as indicating a higher than present-day treeline during the early Holocene (Elias and others, 1991).

Picayne Gulch Bog (3,750 m asl)

The Picayne Gulch bog, at an elevation of 3,750 m, is about 0.7 km downvalley from the head of Picayne Gulch (fig. 2). No conifers presently grow near the bog, which is about 100 m above present-day treeline. The nearest krummholz are about 0.4 km east of the bog at an elevation of 3,650 m, and timberline is about 1.2 km downvalley at an elevation of 3,565 m.

The bog was originally visited in 1972 and a hole was augered to bedrock at a depth of about 200 cm (Andrews and others, 1975, their fig. 3). The stratigraphy consists of alternating layers of peat and clay that contain some organic material. Wood fragments (unidentified) were found at a depth of about 100 cm. A radiocarbon age of 8,430±85 yr B.P. (SI–1558) was obtained from organic material concentrated from the basal clay at 200 cm depth (Andrews and others, 1975).

The Picayne Gulch bog was revisited in 1986 and a pit was hand-dug at a site near the 1972 location; this new pit exposed a section of a very dark grayish-brown (10YR 3/2 wet) peat, 130 cm thick, overlying a greenish-gray (5G 6/1 wet) inorganic clay (fig. 8) (Carrara and others, 1991). Three layers of woody peat were noted at depths of 60–65 cm, 95–105 cm, and 120–130 cm. Wood fragments in these layers were small, usually less than 5 cm long and 1 cm in diameter.

Radiocarbon ages were obtained from two of the woody peat layers (fig. 8, table 4). A radiocarbon age of 6,000±300 yr B.P. (W–5863) was obtained from willow fragments from the woody peat layer at a depth of 95–105 cm. Although this layer contained mainly willow fragments, two small spruce fragments were also recovered. Hence, the radiocarbon age indicates the presence of spruce (probably krummholz) near the Picayne Gulch bog about 6,000 yr B.P. (about 6,850 cal yr), approximately 100 m above present-day treeline. Only willow fragments were found in the woody peat layers at 60–65 cm and 120–130 cm depths; a radiocarbon age of 8,350±250 (W–6013) was obtained from the lower layer.

Discussion

Holocene Treeline and Climatic Fluctuations in the San Juan Mountains

From about 9,200 to 5,800 yr B.P. (about 10,400 to 6,600 cal yr) and possibly as late as 5,400 yr B.P. (about 6,200 cal yr), treeline in the northern San Juan Mountains was at least 80 m higher than at present (fig. 24). This higher treeline is indicated by 66 radiocarbon ages of 53 coniferous wood fragments from the Lake Emma site that form an almost continuous suite of ages during this interval (table 2). Because these wood fragments originated from trees that grew on the surrounding slopes, 80 m is a minimum estimate of the height of early to middle Holocene treeline above its present-day elevation. The highest evidence of treeline above present-day limits came from the Picayne Gulch bog, where, at about 6,000 yr B.P. (about 6,850 cal yr), treeline was at least 100 m higher.

During the period 9,200–5,800 yr B.P. (about 10,400–6,600 cal yr), timberline was also correspondingly higher than present-day, and at 8,000 yr B.P. both treeline and timberline may have been as much as 140 m higher. This higher elevation is indicated by the large spruce fragment from a large, upright tree (Lk Emma 18–81) that yielded a radiocarbon age of 8,010±80 yr B.P. (USGS–1346) (table 2). Because present-day timberline in Eureka Gulch is at an elevation of about 3,600 m, then timberline, and probably treeline as well, was at least 140 m above present-day limits about 8,000 yr B.P. (about 8,900 cal yr).

With the exception of a single spruce fragment radiocarbon-dated at about 3,100 yr B.P. (about 3,300 cal yr), all other coniferous wood fragments (n=52) yielded radiocarbon ages greater than 5,400 yr B.P. (about 6,200 cal yr). Hence, it is unlikely that trees (including krummholz) grew at or above the Lake Emma site during the last 5,400 yr B.P. After this period treeline elevation was probably below Lake Emma, hence, less than 80 m above its present-day limit.

Between 5,400 and 3,500 yr B.P. (about 6,200 and 3,770 cal yr), sparse macrofossil evidence suggests that treeline probably was near its present-day limits. At California Gulch bog (fig. 2), which is only slightly above present-day treeline (fig. 24), radiocarbon ages indicate the continuous presence of spruce from about 7,900 to 3,700 yr B.P. (about 8,700 to 4,050 cal yr). At Eureka Gulch bog, near present-day treeline, a radiocarbon age of 3,905±40 yr B.P. (USGS–2466) (about 4,350 cal yr) (table 4) from organic silty clay containing two

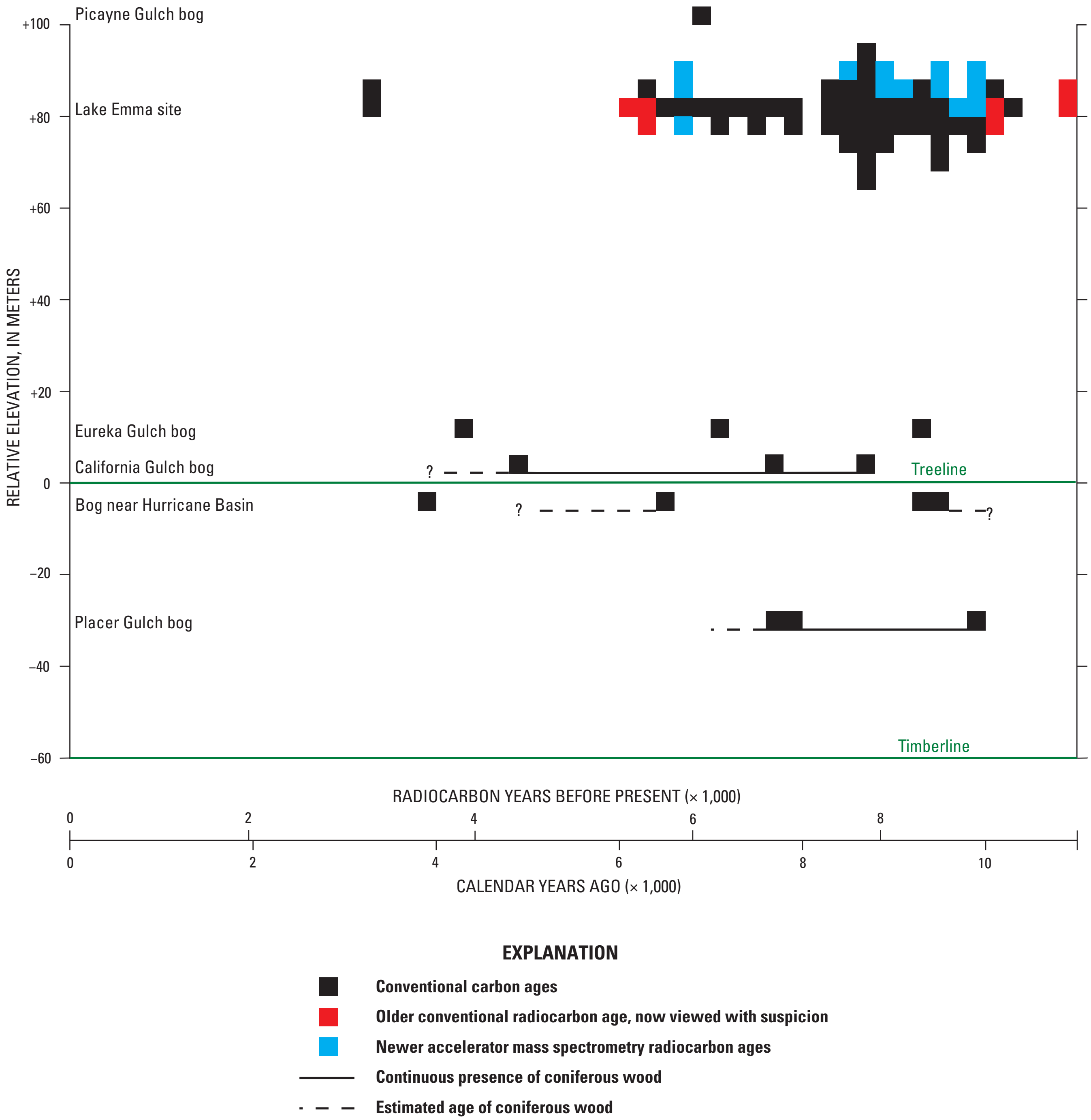


Figure 24. Radiocarbon ages of coniferous wood fragments (squares) from the Lake Emma and other sites in the northern San Juan Mountains and their elevational relation to treeline and timberline. Age of coniferous wood estimated by interpolation or extrapolation of radiocarbon ages. Data for the bog near Hurricane Basin from Andrews and others (1975) and Carrara and others (1991).

small conifer fragments is the only evidence of conifers at this site after 5,400 yr B.P. At the bog near Hurricane Basin (figs. 1, 16), at present-day treeline, a woody peat containing spruce wood, needles, and cone scales yielded a radiocarbon age of about 3,500 yr B.P. (about 3,770 cal yr) (Andrews and others, 1975) (fig. 18), and the age of an underlying peat that contains coniferous macrofossils is estimated to be about 5,600–4,500 yr B.P. (about 6,400–5,150 cal yr) (fig. 24).

Evidence of treeline position after 3,500 yr B.P. (about 3,770 cal yr) is very sparse at all of the bogs discussed earlier, suggesting that treeline lay at a lower than present-day elevation. Two radiocarbon ages of about 3,100 yr B.P. (about 3,300 cal yr) were obtained from a spruce fragment (Stand Metals 01–78) from the Lake Emma site (fig. 21; table 2). The significance of this wood fragment is problematic. The fragment was about 30 cm long and 12 cm in diameter, and it weighed about 1.5 kg (dry weight). It contained about 60 annual rings that had a contorted growth pattern and several lenses of reaction wood that suggest that it was from krummholz. Because this fragment was the only one recovered from the Lake Emma site that yielded a radiocarbon age less than 5,400 yr B.P. (about 6,200 cal yr), it is not clear if the age represents a short-term warm period or if it was simply from a unique krummholz individual that grew in a sheltered niche above the general treeline limit about 3,100 radiocarbon years ago.

As previously mentioned, a unique krummholz individual, now dead, was found on a ridge above California Gulch. Although the tree had grown at an elevation of 3,870 m, about 200 m above the general treeline, it had grown in a sheltered niche at the base of a small south-facing cliff and as such received a sizeable amount of solar radiation. Wood from this individual yielded a radiocarbon age of 280±80 yr B.P. (W–6237), which is outside the calibration range.

A single small conifer fragment found at a depth of 30 cm in the California Gulch bog was estimated by sedimentation rate to date to about 2,400 yr B.P. (about 2,450 cal yr). Again, the interpretation of this single small fragment is also problematic. Pollen data from the bog near Hurricane Basin suggest that treeline after about 3,500 yr B.P. (about 3,770 cal yr) was lower than present-day treeline (Andrews and others, 1975).

The amount of climatic warming responsible for a treeline and timberline rise of at least 80 m and perhaps at least 140 m above present-day limits can be estimated from present-day lapse rates. Because growing-season temperatures are thought to control treeline and timberline (Fritts, 1976; Tranquilli, 1979), an estimate of the amount of warming can be obtained by using a summer lapse rate. Assuming a lapse rate of 6.2°C/km (Barry and Chorley, 1976) a warming of at least 0.5°–0.9°C is estimated for rises of the treeline and timberline ecotones of at least 80 m and 140 m respectively. Additionally, Maher (1961) estimated that the highest postglacial July temperatures in the San Juan Mountains were about 2°C warmer than at present. Combining Maher's (1961) estimate of postglacial temperature rise with the lapse rate of 6.2°C/km (Barry and Chorley, 1976) suggests that, during the early to middle Holocene, the treeline and timberline ecotones may have been more than 300 m higher than at present.

Early Holocene Intensification of the Summer Monsoon?

About 9,000 calendar years ago (about 8,100 radiocarbon yr B.P.), July solar radiation in the Northern Hemisphere is estimated to have been 8 percent greater than at present (Kutzbach, 1987). At that time, summer temperatures are generally thought to have been higher in North America except over and near remaining ice sheets (Kutzbach and Guetter, 1986; Kutzbach, 1987). In places this increase is thought to have exceeded 2°C (Kutzbach, 1987)—an amount similar to Maher's (1961) estimate of postglacial July temperature rise. Because 9,000 calendar years ago summer temperatures were warmer than at present, treeline should also have been higher at that time. Furthermore, because the summer (Arizona) monsoon is driven by a thermal low caused by a heating of desert areas in the American southwest, an increase in July radiation suggests that the summer monsoon circulation was probably more intense during the early Holocene than it is today (Friedman and others, 1988).

Air masses that originate over the Gulf of California and move to the northeast (fig. 3) arrive over the San Juan Mountains without passing over high mountains and thus without accompanying isotopic fractionation of hydrogen. Hence, precipitation from these air masses will have a higher deuterium concentration than precipitation from air masses that originate in the Gulf of Alaska and pass over several ranges before arriving over the San Juan Mountains. Furthermore, a decrease in July radiation from 9,000 calendar years ago to the present should be accompanied by a corresponding decrease in monsoonal activity and, hence, a decrease through time in the concentration of deuterium in water available to trees.

Concentrations of deuterium in the celluose of 18 radiocarbon-dated conifer fragments from the Lake Emma site and in samples of wood from present-day krummholz spruce and fir downvalley from the Lake Emma site were determined (Friedman and others, 1988). The δD was found to have decreased by about 45 per mil from about 9,000 to 3,100 yr B.P. (about 10,150 to 3,300 cal yr) and by an additional 25 per mil from 3,100 yr B.P. to the present. This decrease in deuterium concentration was interpreted as indicating a major change during the Holocene in the sources of moisture or in the seasonality of precipitation (or both), and suggested that the summer monsoon was more intense (that is, wetter) during the early Holocene (Friedman and others, 1988).

However, all sources of moisture available to Lake Emma, including the northern Pacific and the Gulfs of Alaska, Mexico, and California, would have been affected by early to middle Holocene warming (Epstein and others, 1999). Hence, moisture derived from any of these sources during this period would have had a higher δD value. Therefore, the decrease in deuterium concentration, although suggesting the possibility of more intense monsoonal flow during the early to middle Holocene, cannot be distinguished from the effect of warmer global temperatures.

However, support for an early Holocene intensification of the summer monsoon was found in central Colorado (Markgraf and Scott, 1981). The climate changed from cool and moist before 10,000 yr B.P. (about 11,500 cal yr) to warm and moist about 10,000–4,000 yr B.P. (about 11,500–4,450 cal yr). Evidence for this climatic shift is based on pollen changes in an erosional cut near the town of Crested Butte, about 120 km north of the Lake Emma site and suggests that a northward shift of the summer monsoon pattern about 10,000 yr B.P. increased summer precipitation and summer temperatures (Markgraf and Scott, 1981). A shift to a warm and dry climate with fewer monsoon events after about 4,000 yr B.P. resulted in the present-day climatic regime in which precipitation in the area is partially monsoonal and partially derived from Pacific storms originating in the Gulf of Alaska (Markgraf and Scott, 1981).

Similar conclusions, based on pollen and plant macrofossil analysis, were also reached by Fall (1997), who found that between about 9,000 and 4,000 yr B.P. (about 10,150 and 4,450 cal yr) the climate of central Colorado was both warmer and wetter (owing to intensification of the summer monsoon) than at present. At that time spruce-fir forest covered a broader elevation range than today. Upper timberline was higher than at present suggesting that summer temperatures were about 2°C warmer than at present (Fall, 1997). Conversely, the lower limits of the montane and subalpine forests were lower than at present suggesting an annual precipitation about 80–100 mm greater than at present.

Because lake levels in the southwest, thought to be controlled by winter precipitation, were lower during the early and middle Holocene than at present, Shuman and others (2009) concluded that summer precipitation was a greater proportion of the total precipitation during this period.

Finally, estimates of even larger Holocene temperature change were obtained by Epstein and others (1999). Concentrations of deuterium in the celluose of 39 radiocarbon-dated conifer fragments from the Lake Emma site were determined (Epstein and others (1999, their fig 1). For any given period a range of values of δD was obtained. The highest δD values were thought to represent those trees growing at Lake Emma, whereas the lowest δD values represent those trees growing at treeline (at the highest elevation and lowest temperature) above Lake Emma. For instance, for those trees radiocarbon dated at about 9,000 yr B.P. (about 10,150 cal yr), δD values ranged from a high of about −30 per mil (trees growing at Lake Emma) to a low of about −63 per mil (treeline above Lake Emma) (Epstein and others, 1999; their fig. 1)). The δD range and the maximum δD value, decrease as the ages of the samples decrease. Hence, the temperature (and treeline) in the Lake Emma cirque was highest about 9,000 yr B.P. and thereafter progressively decreased with time. If we assume that the coefficient relating temperature and δD values is 8 per mil/°C (Yapp and Epstein, 1982), then the maximum average climatic temperature change from about 9,000 to 5,400 yr B.P. (about 10,150 to 6,200 cal yr), to when treeline dropped below Lake Emma, was about 4°C (Epstein and others, 1999).

Conclusions

Shortly after deglaciation of the Molas Lake site, organic sediments began to accumulate from which pollen data, including spruce/pine ratios, were developed. These data suggest that the average July temperature was about 5°C cooler and timberline was about 650 m lower than at present (Maher, (1961), or at an elevation of about 2,885 m (fig. 25). Unfortunately, the radiocarbon ages from the Molas Lake core associated with this period may have been subject to a hard-water effect (L.J. Maher Jr., oral commun., 1983), yielding radiocarbon ages older than the true age of the sediment. On the basis of information discussed in this report, the minimum age of this initial organic sediment may be about 10,450 yr B.P. (about 12,300 cal yr).

At Black Mountain Lake, an unglaciated site about 100–150 m below present-day timberline, evidence suggests that timberline was at or above the site by about 11,400 yr B.P. (about 13,250 cal yr). It then declined about 60–120 m during the Younger Dryas interval, but by about 10,000 yr B.P. (about 11,500 cal yr) had readvanced to elevations at or above the site (Reasoner and Jodry, 2000) (figs. 1, 5). These data suggest that trees may have been present near the Black Mountain Lake site during the Pinedale glaciation, much as forest surrounds the tongues of glaciers in present-day Alaska.

Forestation of formerly glaciated valleys in the San Juan Mountains was underway by about 11,000 yr B.P. (about 12,900 cal yr) (fig. 25). This forestation is indicated by the radiocarbon ages of coniferous wood fragments from the well site near the town of Telluride, about 10 km upvalley from the Pinedale terminal moraines of the San Miguel glacier.

Between about 9,200 and 5,400 yr B.P. (about 10,400 and 6,200 cal yr) treeline was at least 80 m higher than at present (fig. 25). The highest evidence of conifer establishment, a spruce fragment, was found at the Picayne Gulch bog (fig. 2) and yielded a radiocarbon age of about 6,000 yr B.P. (about 6,850 cal yr) indicating the presence of spruce at least 100 m above present-day treeline at that time. In addition, a radiocarbon age from a large conifer fragment with a complacent annual ring record suggests that timberline may have been at least 140 m above its present-day elevation about 8,000 yr B.P. (about 8,900 cal yr) at Lake Emma. A warming of at least 0.5°–0.9°C is estimated from a rise in treeline and timberline of 80 and 140 m, respectively. Because these rises are minimum values, estimates of the amount of warming are also minimum values. Indeed, Epstein and others (1999) suggested that the average temperature change from about 9,000 to 5,400 yr B.P. (about 10,150 to 6,200 cal yr), when treeline dropped below Lake Emma, was about 4°C.

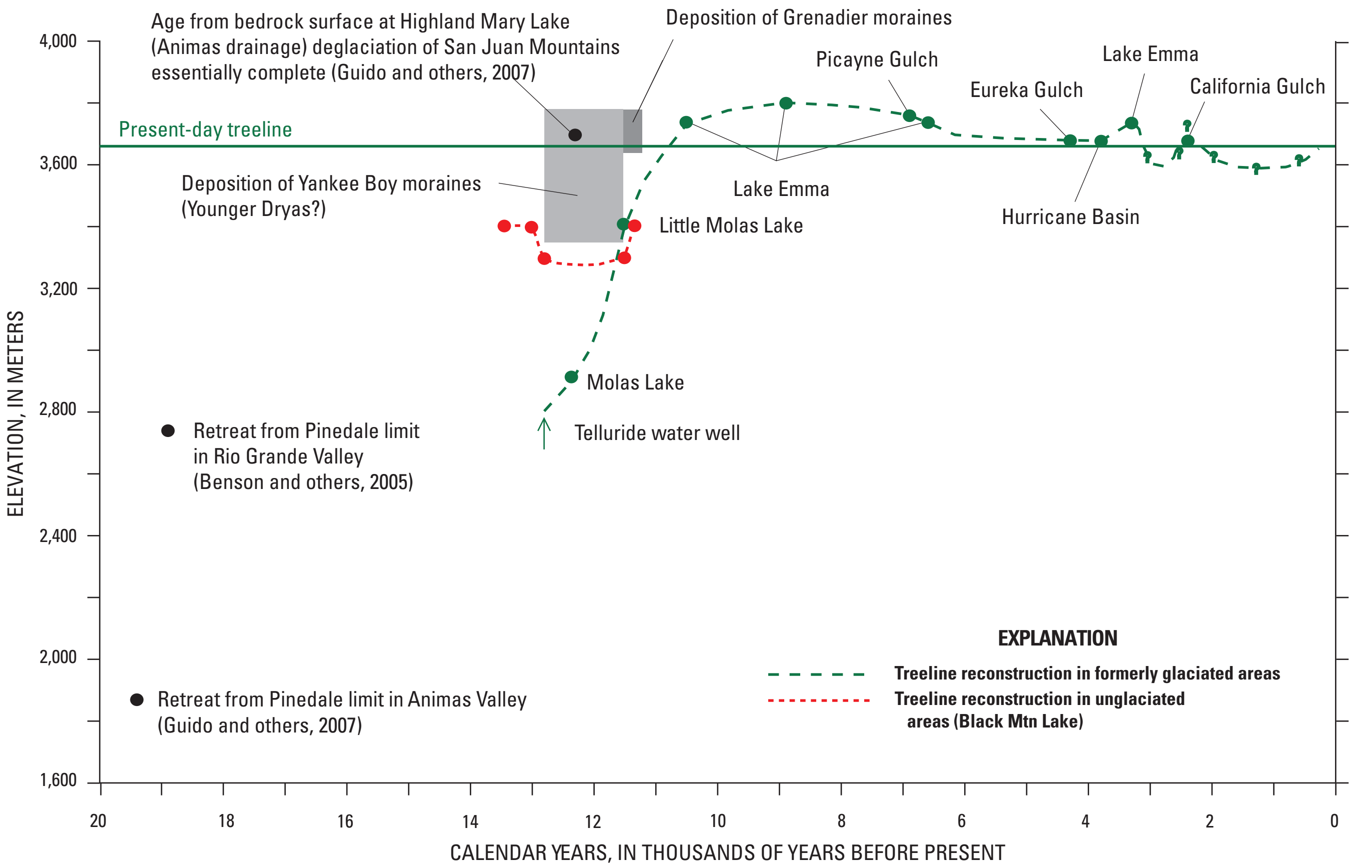


Figure 25. Timeline of events in the San Juan Mountains showing initial timing of Pinedale glacial retreat, deglaciation of the range, deposition of the Yankee Boy and Grenadier moraines, and treeline fluctuations from the late Pleistocene through the Holocene.

Between about 5,400 and 3,500 yr B.P. (about 6,200 and 3,770 cal yr) evidence of treeline elevation is sparse, but it appears that during this period treeline was near its present-day limit. This conclusion is based on the lack of coniferous macrofossils at the two highest sites (Lake Emma and Picayne Gulch) and the presence of macrofossils at several of the sites at or near present-day treeline (Eureka Gulch, California Gulch, and Hurricane Basin) (figs. 1, 2).

After 3,500 yr B.P. (about 3,770 cal yr) evidence of treeline position is very sparse, suggesting that treeline lay at a lower than present-day elevation. However, two radiocarbon ages of about 3,100 yr B.P. (about 3,300 cal yr) were obtained from a spruce krummholz fragment from the Lake Emma site. Because these radiocarbon ages are the only ones from this period at the Lake Emma site, it is not clear if this wood fragment represents a short-lived climatic amelioration or if it came from a unique krummholz individual that grew above the general treeline limit at that time. In addition, a small conifer fragment at a depth of 30 cm in the California Gulch bog was estimated by sedimentation rate to date from about 2,400 yr B.P. (about 2,450 cal yr). Again, the interpretation of this fragment is difficult.

The summer monsoon circulation that currently brings a large part of the annual precipitation to the San Juan Mountains probably was more intense during the early and middle Holocene. This intensification may be indicated by the higher than present-day deuterium concentrations in the early to middle Holocene-age wood fragments from the Lake Emma site (Friedman and others, 1988) and pollen evidence from surrounding regions.

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Appendix A
Evidence of Higher Treelines During the Holocene in Western North America, as Indicated by Radiocarbon Ages or Cross-Dated Conifer Remains

Introduction

In addition to those sites in the San Juan Mountains discussed above, other sites throughout western North America (fig. A–1) have yielded conifer remains above present-day limits demonstrating treelines higher than at present throughout much of the Holocene. This evidence consists of conifer fragments, needles, and cones recovered from lakes and bogs; remnant conifer fragments lying on the surface or emerging from shrinking snowbanks; and standing dead snags above present-day limits. These remains were commonly radiocarbon dated and in some cases cross-dated by dendrochronology, yielding very precise dates. The results of many of these studies are similar to those obtained from the San Juan Mountains, and they indicate a higher than present-day treeline during the early to middle Holocene. Moreover, several studies also indicate a higher treeline extending into the late Holocene (Lamarche and Mooney, 1972; LaMarche, 1973; and K.L. Pierce, oral commun., 1989). In the discussion below, approximately 20 of these sites are documented.

Figure A–1 Sites of Holocene conifer fragments above present-day treeline in western North America.

Front Range, Colorado

Several sites in the Colorado Front Range (fig. A–1) provide evidence of a timberline similar to or higher than at present during the early Holocene. In the Caribou Lake valley west of the Continental Divide, timberline is presently at an elevation of about 3,350–3,400 m, and treeline is about 3,450 m (Benedict, 1985). A log recovered from a bog at an elevation of 3,400 m yielded a radiocarbon age of 9,200±135 yr B.P. (I–6520) (Benedict, 1973, 1985; locality 12). The age was interpreted to indicate that timberline had risen either to, or above, its present elevation by about 9,200 yr B.P. (about 10,400 cal yr) (Benedict, 1973, 1985). Radiocarbon ages of 9,915±165 yr B.P. (laboratory number I–6335) and 9,700±215 yr B.P. (I–6336) from a basal peat containing spruce needles from this same bog suggests that treeline may have risen to about its present-day limit by about 9,900 yr B.P. (about 11,300 cal yr) (Benedict, 1985).

At another site in the Caribou valley evidence also indicates an early Holocene timberline elevation similar to that at present. Radiocarbon ages of 9,720±220 yr B.P. (I–12198A) and 9,520±160 yr B.P. (I–12198B) (weighted average 9,590±130 yr B.P.) were obtained from basal samples of humus-rich silt, spruce cones, and wood fragments (Benedict, 1985, locality H). The samples were recovered from a small bog at the forest-tundra ecotone at an elevation of 3,395 m and were interpreted as indicating that mature spruce trees grew near the bog and, hence, near present-day timberline at this time (about 10,950 cal yr) (Benedict, 1985).

In the Mummy Pass area of Rocky Mountain National Park evidence of a higher than present-day timberline during the middle Holocene was also found. Here, trunks of full-sized trees (*Picea engelmanni*) were found emerging from the melting edge of a snowbank in a northeast-facing recess at an elevation of 3,475 m, just below the modern tree limit (Benedict and others, 2008). Radiocarbon ages of the outer growth rings of four of these trees ranged between 3,860±15 yr B.P. (CURL−8892) and 3,780±20 yr B.P. (CURL−8884) and indicated that their date of death was about 4,200 calendar years ago (Benedict and others, 2008). The trunks were interpreted as indicating that forest vegetation grew on the present-day tundra during this time and that regional timberline was at least 100–150 m higher than at present (Benedict and others, 2008).

Sawatch Range, Colorado

In the Cottonwood Pass area of the Sawatch Range (fig. A–1) in central Colorado, a sediment core was taken from a small pond at an elevation of 3,670 m (Fall, 1997). On the basis of pollen and plant macrofossil analysis of this core and accompanying radiocarbon ages, Fall (1997) concluded that between about 9,000 and 4,000 yr B.P. (about 10,150 and 4,450 cal yr) the climate of central Colorado was both warmer and wetter than at present. Fall (1997) also concluded that upper timberline was 270 m higher and that mean annual and mean July temperatures were 1°–2°C warmer than at present during this period. However, during a visit to Cottonwood Pass Pond in July 2009, the author noted full-sized spruce encroaching upon the pond, such that the pond is no more than 30 m above present-day timberline and scattered patches of krummholz extend at least 50 m above this site. Hence, Fall's estimate of an early Holocene timberline 270 m above that of the present appears to be too high.

Sangre de Cristo Mountains, Colorado

Lake Como, at an elevation of 3,580 m, is in a glacial valley on the west side of the Sangre de Cristo Mountains (fig. A–1), about 110 m below present-day timberline (Jodry and others, 1989; Shafer, 1989). Here, a 300-cm sediment core was collected and analyzed for pollen and plant macrofossils. High percentages of *Artemisia* pollen (>60 percent) in late Pleistocene assemblages were interpreted as evidence of widespread sagebrush (*Artemisia tridentata*) in the adjacent San Luis Valley to the west. A radiocarbon age of 10,260±230 yr B. P. (A-04895) was obtained from spruce macrofossils at a depth of 240–250 cm and indicate that by this time trees (full-sized or krummholz?) were growing by the lake (Jodry and others, 1989; Shafer, 1989). The abundance of macrofossils of Engelmann spruce, bristlecone pine, and subalpine fir suggests that upper treeline reached its highest elevation about 10,000–9,000 yr B.P. (about 11,525–10,150 cal yr). In addition, comparison of spruce/pine ratios in the pollen of the Lake Como core with modern spruce/pine ratios suggests that timberline around Lake Como was about 175–203 m higher than today in the earliest Holocene (Jodry and others, 1989; Shafer, 1989).

Wind River Range, Wyoming

In the Temple Lake area in the southern Wind River Range (fig. A–1) a radiocarbon age of 3,520±155 yr B.P. (GX–2748) was obtained from a bog at an elevation of 3,260 m, 0.1 km downvalley of Temple Lake (Currey, 1974). The bog, on the inner moraine of the type Temple Lake moraine, contained well-preserved plant debris such as wood fragments and conifer needles (Currey, 1974). In this valley the upper limit of continuous forest lies at an elevation of about 3,135 m, scattered stands of trees grow up to about 3,200 m (Fall and others, 1995), and patches of dwarf (krummholz) whitebark pine and Engelmann spruce extend to about 3,230 m. The nearest trees to the bog site are about 0.5 km downvalley. The radiocarbon age (about 3,800 cal yr) was thought to "represent a time when the site was more suitable for conifer growth, perhaps warmer and drier than at present" (Currey, 1974).

An additional radiocarbon age of 3,825±230 yr B.P. (GX–11700) was obtained from unidentified conifer needles and wood fragments between 78 and 81 cm depths in a core from Miller Lake (Zielinski, 1989; Fall and others, 1995), approximately 0.5 km downvalley from Currey's (1974) bog site. This radiocarbon age (about 4,200 cal yr), along with pollen analyses, led Fall and others (1995) to conclude that during much of the Holocene, treeline was probably at least 100 m higher than today.

Finally, large standing snags were observed in 1938 above timberline (3,200 m elevation) on the northern side of Shale Mountain between Ross and Simpson Lakes in the northern Wind River Range (G.M. Richmond, oral commun., 1989). The site has not been revisited for collection of samples to be radiocarbon dated.

Yellowstone National Park, Wyoming

On the northeast side of Mount Washburn in Yellowstone National Park (fig. A–1), wood (probably from krummholz whitebark pine) was found lying on alpine tundra (K.L. Pierce, oral commun., 1989). The area is at an elevation of about 3,015 m, approximately 25 m above present-day treeline. Radiocarbon ages of three fragments yielded ages of 830±70 yr B.P. (W–4239), 1,060±200 yr B.P. (W–4154), and 1,190±60 yr B.P. (W–4240) (K.L. Pierce, oral commun., 1989), suggesting a warmer than present-day climate corresponding with the Medieval Warm Period (about 800 to 1,300 AD).

La Sal Mountains, Utah

Although no precise location is given, Richmond (1962, p. 15) mentions that a possible higher timberline in the past is suggested by local stands of dead, gnarled, and twisted relatively large trees in the La Sal Mountains (fig. A–1) that extend farther upslope from the present-day forest than the upper limit of new growth.

West Mountains, Idaho

In a cirque in the West Mountains of west-central Idaho (fig. A–1), a radiocarbon age of 11,540±70 yr B.P. (WW–443) was obtained from a small spruce cone overlying a Glacier Peak ash in a bog at an elevation of 2,255 m (Doerner and Carrara, 1999). In this mountain range, timberline is at an elevation of about 2,285 m and is dominated by subalpine fir and whitebark pine, while treeline is at an elevation of about 2,380–2,500 m. However, the present-day limit of Engelmann spruce is at an elevation of about 2,250 m. It is not clear whether the small spruce cone recovered from the bog came from a full-sized tree or a krummholz form; nonetheless, by about 11,540 yr B.P. (about 13,400 cal yr) spruce was already near its present-day elevation limits.

Beartooth Mountains, Montana

In the Grass Mountain area of the Beartooth Mountains (fig. A–1), radiocarbon ages of 7,935±15 yr B.P. (CURL−8843) and 7,955±15 yr B.P. (CURL−8845) were obtained from two rooted stumps of Engelmann spruce emerging from the melting edge of a snowbank (Lee, 2006). Because this snowbank is presently above treeline, the radiocarbon ages indicate a time (about 8,800 cal yr) of higher than present-day treeline and warmer climate. Additional discoveries of subfossil trees emerging from retreating snowbanks were also made on the Silver Run and Hell Roaring Plateaus (Lee, 2006).

Snake Range, Nevada

On Mount Washington in the Snake Range of east-central Nevada (fig. A–1), 14 radiocarbon ages were obtained from 13 standing dead snags and remnants of bristlecone pine lying on the ground above present-day limits (LaMarche and Mooney, 1972). Living bristlecone pines at this site show a progressive gradation from tall, erect trees in the upper forest zone to dwarfed, prostrate krummholz at higher elevations. LaMarche and Mooney (1972) determined that a similar gradation existed from 4,000 yr B.P. to at least 2,000 yr B.P. (about 4,450 to at least 1,950 cal yr), but that the boundaries between the tree forms were at least 100 m higher than today. Because an indeterminate amount of wood had been eroded from the original outside and pith parts of many of these remnants, this time span represents a minimum estimate of the time during which the treeline was higher than at present.

White Mountains, California

Two locations in the White Mountains of California (fig. A–1) were investigated by LaMarche (1973). On the basis of both radiocarbon ages and cross-dating of bristlecone pine remnants above present-day treeline he concluded that on Campito Mountain treeline was 70 to 110 m above the modern treeline from about 7,400 yr B.P., the beginning of his record, to about 800 yr B.P. (LaMarche, 1973, his fig. 17). On nearby Sheep Mountain, where the oldest remnant dated back to about 5,600 yr B.P., treeline was determined to be about 50–150 m above the modern limit from 5,600 to 800 yr B.P. (LaMarche, 1973, fig. 17). Lamarche (1973) cautioned that his estimates of higher treeline positions should be considered minimum values in that remnants higher than those collected may have existed at one time but may have disintegrated with time.

Sierra Nevada, California

At Cirque Peak in the southern Sierra Nevada of California (fig. A–1), Scuderi (1987) used a combination of radiocarbon ages and cross-dating of foxtail pine (*Pinus balfouriana*) remnants to determine timberline fluctuations since 6,300 yr B.P. Scuderi (1987) found that timberline descended from a high at 6,300 yr B.P. to a low at 900 yr B.P. Between 6,300 and 3,300 yr B.P. (about 7,200 and 3,500 cal yr) timberline was about 70 m higher than the present-day limit. From 3,300 to 2,400 yr B.P. (about 3,500 to 2,450 cal yr) it was about 35 m above the present limit; from 2,400 to 1,300 yr B.P. (about 2,450 to 1,250 cal yr) it was 12 m above the present limit; from 1,300 to 900 yr B.P. (about 1,250 to 800 cal yr) it was below the present limit; and since 900 yr B.P. timberline has been at its present limits (Scuderi, 1987).

Jasper National Park, Alberta, Canada

In the southern Canadian Cordillera, several sites at or above present-day treeline have yielded coniferous wood fragments. Radiocarbon ages of these fragments are in general agreement with those from the Lake Emma site. In the Maligne Range, Jasper National Park, Alberta (fig. A–1), timberlines were at least 100 m, and possibly as much as 200 m, higher than at present between about 8,800 and 5,200 yr B.P. (Kearney and Luckman, 1983; Luckman and Kearney, 1986). This conclusion was based in part on five radiocarbon ages from spruce and fir fragments recovered from the Watchtower Basin and the Maligne Pass area, both of which are about 50–100 m above present-day timberline. The wood fragments from the Watchtower Basin displayed a complacent growth record. On the basis of the radiocarbon ages and pollen data from Watchtower Basin and the nearby Excelsior Basin, Kearney and Luckman (1983) concluded that during the early and middle Holocene there were two periods of higher timberline: the first from about 8,800 to 7,500 yr B.P. (about 9,800 to 8,300 cal yr) and the second from about 7,200 to 5,200 yr B.P. (about 8,000 to 5,950 cal yr). These periods of higher timberline were separated by a period when timberline was near its present elevation. After about 4,500 yr B.P. (about 5,150 cal yr) timberline has been similar to or lower than at present, and it reached its lowest limit within the last 500 yr (Kearney and Luckman, 1983; Luckman and Kearney, 1986).

Coast Mountains, British Columbia

In the southeastern Coast Mountains of British Columbia (fig. A–1), timberline was at least 60 m and perhaps more than 130 m higher than at present between about 9,100 and 8,200 yr B.P. (about 10,250 and 9,150 cal yr) (Clague and Mathewes, 1989). This higher timberline is indicated by five radiocarbon ages from fir and pine fragments found above present-day timberline in a cirque in the Castle Peak area. Using present-day lapse rates, Clague and Mathewes (1989) estimated that the mean summer temperature during this period was 0.4°–0.8°C warmer than at present.

Clague and Mathewes (1989, their table 2) also presented 29 radiocarbon ages from conifer and charcoal fragments collected from various sites at or above present-day timberline in southern British Columbia and the adjacent Jasper National Park area of Alberta. These radiocarbon ages ranged from about 9,100 to 4,400 yr B.P. (about 10,250 to 5,000 cal yr). If only the 16 radiocarbon ages from above timberline are considered, the ages range from about 9,100 to 5,300 yr B.P. (about 10,250 to 6,075 cal yr), similar to the ages from the Lake Emma site.

One group of radiocarbon ages in the Clague and Mathewes (1989, their table 2) study fell between about 9,100 and 7,600 yr B.P. (about 10,250 and 8,400 cal yr), whereas a second group of radiocarbon ages fell between about 6,600 and 5,100 yr B.P. (about 7,500 and 5,850 cal yr). Hence, the two groups of radiocarbon ages are separated by about a thousand-year interval. Timberline may have been at a lower elevation during this period; however, Clague and Mathewes (1989) thought it equally possible that this long interval could simply be a consequence of the small size of their data set. The first 22 radiocarbon ages from coniferous wood fragments from the Lake Emma site also contained a gap (Carrara and others, 1984). One group of 15 ages fell between about 9,600 and 7,800 yr B.P., and a second group of 6 ages fell between about 6,700 and 5,400 yr B.P. Hence, these two groups of radiocarbon ages were separated by an interval of about 1,100 years. Of the 44 subsequent radiocarbon ages, 11 fall within this 1,100-yr interval (table 2). Therefore, in the case of the Lake Emma site, the interval in which no radiocarbon ages were initially obtained (Carrara and others, 1984) was a consequence of the small size of the original data set and not of a lower treeline.

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