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R. Scott Anderson,[1,2]
Jim Hasbargen,[2,3]
Peter A. Koehler,[2,4] *and*
Eric J. Feiler[2,5]

[1]Center for Environmental Sciences and Education, Box 5694, Northern Arizona University, Flagstaff, Arizona 86011, U.S.A.
Scott.Anderson@nau.edu
[2]Quaternary Studies Program and Bilby Research Center, Box 6013, Northern Arizona University, Flagstaff, Arizona 86011, U.S.A.
[3]Present Address: SWCA, Inc., 114 N. San Francisco, Flagstaff, Arizona 86001, U.S.A.
[4]Present Address: P.O. Box 861, Flagstaff, Arizona 86002 U.S.A.
[5]Present Address: PaleoCultural Research Group, P.O. Box EE, Flagstaff, Arizona 86002, U.S.A.

Abstract

The vegetation and climatic history of subalpine forests on the Colorado Plateau is documented from Lowder Creek Bog and Alpine Pond on the Markagunt Plateau. Pollen and macrofossil data demonstrate substantial changes at sites above 3150 m elevation during the last ca. 13,000 yr. During and after Late Wisconsin deglaciation, subalpine tree species (*Picea engelmannii* and *Abies lasiocarpa*) were rare or absent near the Lowder Creek Bog site, but nonarboreal species predominated. *P. engelmannii–A. lasiocarpa* forest became well-established there between 11,000 and 9800 yr BP and subalpine trees dominated this elevation throughout the Holocene. By ca. 8500 yr BP, however, *Picea* declined somewhat, with minimal pollen and macrofossil deposition occurring between ca. 8500 and 6400 yr BP. *Picea* trees may have thinned during this time or *Picea* may have expanded to higher elevations during this part of the Holocene, while *Pinus ponderosa* expanded at lower elevations. These changes were probably driven by warmer conditions with variable precipitation. Alternative explanations include hydroseral changes within the bog, or insect infestation on *Picea.* After ca. 6400 yr BP, more consistent *Picea* pollen influx suggests renewed importance around the bog, which has been maintained until the present. *Abies lasiocarpa* became more important after ca. 2700 yr ago.

The pollen sequence supports an interpretation of high effective precipitation during the early Holocene, followed by warmer temperatures and somewhat variable precipitation after ca. 8500 yr BP. This sequence is most similar to other sites on and near the western, southern, and northeastern Colorado Plateau, where the maximum influence of monsoon activity may have declined by the end of the early Holocene. Declines in summer insolation probably contributed to Late Holocene cooling, with increasing effective precipitation at most sites, including Lowder Creek Bog.

Introduction

The Colorado Plateau is a well-defined physiographic feature in western North America, between the Basin and Range province to the west and south and the Rocky Mountains to the east and north. The Colorado Plateau consists of a series of raised uplands or individual smaller plateaus, in aggregate covering ca. 337,000 km² (Fig. 1). Much of the Plateau is composed of flat-lying sedimentary rocks separated by incised canyons of varying width and depth. Mountain ranges, often of volcanic origin, occur interspersed throughout the Plateau (Hunt, 1967). Although elevations range from 4600 to 1000 m above sea level, nearly half of the Plateau lies below 1850 m (Betancourt, 1990).

Climatic patterns vary from south to north across the Colorado Plateau. Much of the northern Colorado Plateau shares a climatic regime with the Great Basin. This region generally lies outside the typical major pathways of winter and summer moisture-bearing air masses (Mitchell, 1976; Petersen, 1994). Winter moisture comes from Pacific air masses, and summers are generally hot, with infrequent rainfall from convective storms. The southern Colorado Plateau, however, has a distinct biseasonal precipitation regime. Winter precipitation arrives from incursions of Pacific air, while summer precipitation is monsoonal, with a moisture source to the south, southwest, or southeast (Mitchell, 1976; Petersen, 1994; Mock, 1996). This climatic gradient has led to development of a vegetation gradient as well, with species more dependent upon summer precipitation occurring dominantly in the southern and southeastern Colorado Plateau (Jackson et al., unpublished), declining toward the northwest. Locally, these generalizations are modified by high topographic diversity.

Here we examine two records from small basins within the subalpine zone of the Markagunt Plateau in southwestern Utah, and place these records in context with our knowledge about similar forests elsewhere. The 13,000-yr record from the Markagunt Plateau sites is important for several reasons. First, these sites occur on the boundary between the Great Basin and the Colorado Plateau. Analyses should assist in interpretation of vegetation change over this longitudinal gradient. Second, our knowledge of subalpine environments on the Colorado Plateau is limited. The records from Lowder Creek Bog and Alpine Pond provide an important linkage to other studies from high-elevation sites on or near the margins of the Colorado Plateau (Madsen and Currey, 1979; Anderson, 1993; Hasbargen, 1994; Fall, 1997; Feiler et al., 1997; Weng and Jackson, 1999). Third, additional high-elevation sites are necessary to complete the emerging picture of vegetation change deduced from the lowland elevations of the Great Basin and Colorado Plateau, largely from packrat midden evidence (Betancourt, 1990; Thompson, 1990;

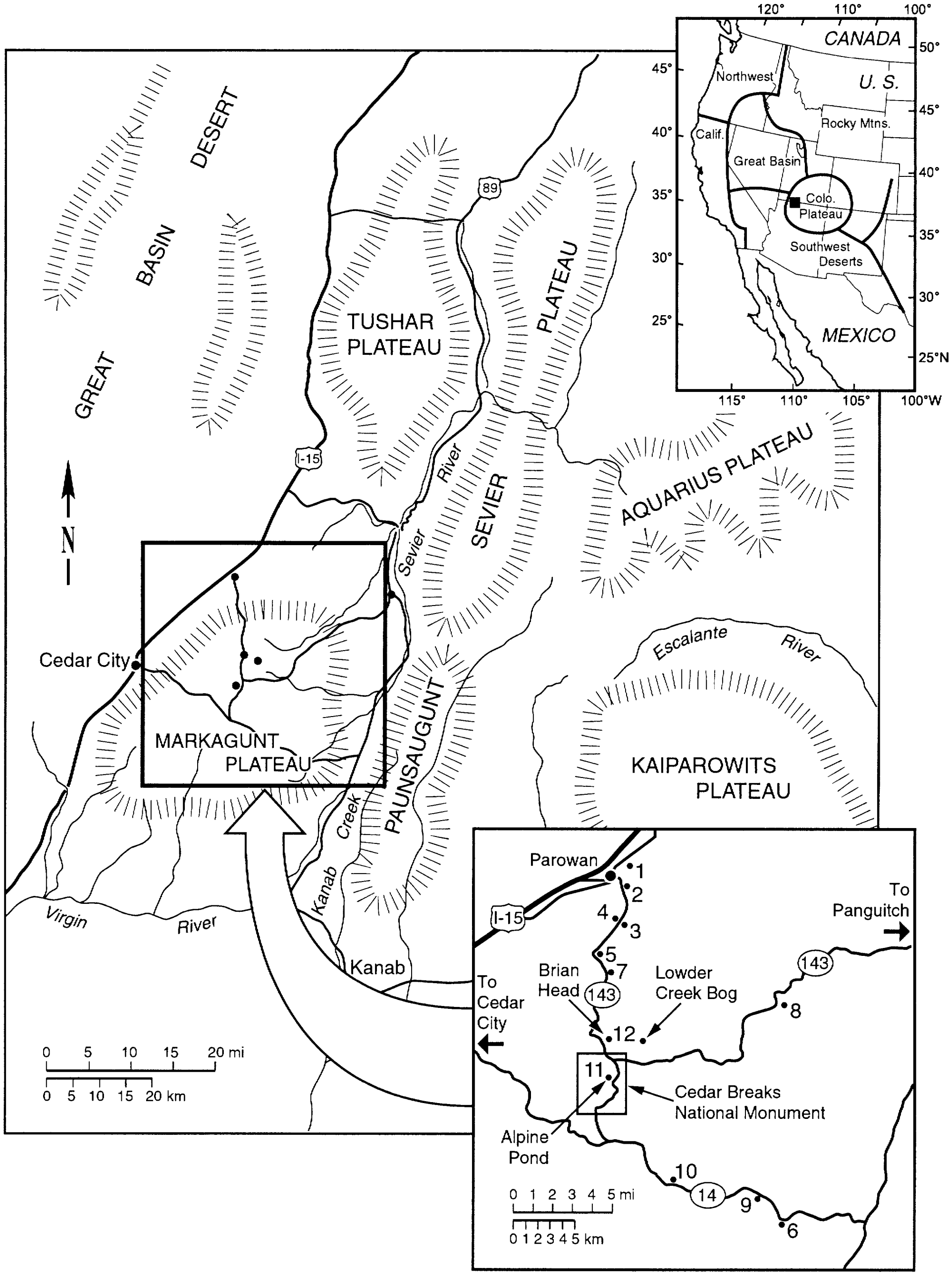

FIGURE 1. Location of Lowder Creek Bog and Alpine Pond on the Markagunt Plateau, southwestern Utah, along with adjacent High Plateaus of the southern Colorado Plateau. Small inset on the lower right shows the numbered locations of modern pollen samples (moss polsters), which are keyed to site descriptions in Table 2.

Anderson et al., 1999). Last, the paleovegetation record from Lowder Creek Bog is shown to be a sensitive indicator of environmental change. The occurrence of these two sites near the northern extreme of the modern monsoonal precipitation boundary, as shown by Mitchell (1976), is significant in this regard. The emerging synthetic picture is providing a greater understanding of this region of sparse, but growing population, and vast recreational and economic interests.

The Study Area

Lowder Creek Bog and Alpine Pond occur on the Markagunt Plateau of southwestern Utah, one of several High Plateaus (Wasatch, Paunsaugunt, Sevier, Aquarius, Kaiparowits) which form the western boundary of the Colorado Plateau (Hunt, 1967). The Markagunt Plateau is bounded on the west and north by the Hurricane Fault and the Great Basin, on the east by the Sevier Fault and the Sevier River, and on the south by the Virgin River (Fig. 1). Much of the exposed bedrock on the Plateau is the weakly indurated Paleocene Claron Formation, a series of colorful, carbonate-rich lakebeds (Chronic, 1990). Subsequent uplift has raised the Plateau to average elevations above ca. 2750 m. The highest elevation on the Plateau is Brian Head (3446 m), composed of Oligocene lava flows and tephras.

Modern climatic data for the Markagunt Plateau are sparse. A 6-yr precipitation and temperature record from the Brian Head station (2980 m; latitude 37°41′N, longitude 112°50′W) (NOAA, 1991–1997) near Lowder Creek Bog documents cold winters and

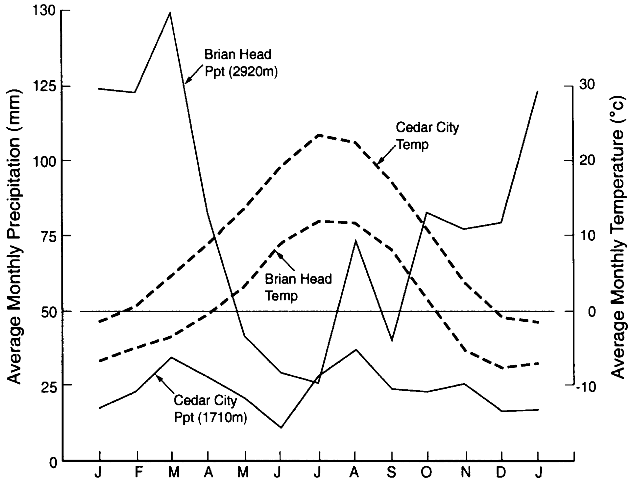

FIGURE 2. Average monthly precipitation (mm) and temperature (°C) for two stations near the study sites. The Brian Head station (37°41'N; 112°50'W; 2980 m elevation) consists of a 6-yr record. The Cedar City station (37°42'N, 113°06'W; 1710 m elevation) contains a 51-yr record (NOAA, 1991–1997). See Figure 1 for specific station locations.

moderate summers. Maximum precipitation occurs as snow during January through March, with a secondary peak in August due to monsoonal precipitation (Fig. 2). June and July are the driest months of the year. A 51-yr record from Cedar City, Utah (1710 m; 37°42'N, 113°06'W), ca. 25 km west of Lowder Creek Bog documents moderate winters with hot summers (Fig. 2). Two peaks in precipitation occur there—in early spring and in August associated with the summer monsoon. June is the driest month at this station.

Modern vegetation of the higher elevations of the Markagunt Plateau region has been described by Dixon (1935), Betancourt (1990), Buchanan (1992), and others. The alpine zone generally occurs above 3480 m, where *Castilleja parvula* (Tushar paintbrush), *Eriogonum umbellatum* (sulfur buckwheat), *Phlox pulvinatum* (cushion phlox), *Potentilla concinna* (pretty cinquefoil), *Oxytropis oreophila* (mountain locoweed), and *Ribes montigenum* (alpine prickly currant) are conspicuous. Common trees and shrubs in the closed subalpine zone (ca. 2900–3480 m) include *Abies lasiocarpa* (subalpine fir), *Picea engelmannii* (Engelmann spruce) and *Juniperus communis* (common juniper). Subalpine meadows may support a variety of species including *Viola nephrophylla* (bog violet), *Primula parryi* (Parry primrose), *Gentianopsis detonsa* (meadow gentian), among others.

A mixed conifer forest occurs from ca. 2600 to 2900 m, and can include *Abies concolor* (white fir), *Pseudotsuga menziesii* (Douglas-fir), *Picea pungens* (blue spruce), *Populus tremuloides* (quaking aspen), with *Picea engelmannii, A. lasiocarpa, Pinus ponderosa* (ponderosa pine), *Mahonia repens* (Oregon grape), and *Sambucus cerulea* (blue elderberry). The ponderosa pine forest (2100–2600 m) is dominated by *P. ponderosa* with *Juniperus scopulorum* (Rocky Mountain juniper), *Purshia tridentata* (bitterbrush), *Prunus virginiana* (chokecherry), *Ceanothus martinii* (Utah mountain lilac), *Ribes cereum* (wax currant), and *Symphoricarpos oreophilus* (mountain snowberry), among others. In the frequent valley bottoms at this elevation can be found *Artemisia nova* (black sagebrush), *Chrysothamnus depressus* (dwarf rabbitbrush), *Hymenoxys richardsonii* (Colorado rubber plant), and *Potentilla fruiticosa* (shrubby cinquefoil).

The piñon-juniper woodland occupies extensive areas between ca. 1600 and 2100 m elevation, and includes *Pinus edulis* (two-needled piñon), *Juniperus osteosperma* (Utah juniper), *Amelanchier utahensis* (Utah serviceberry), *Chrysothamnus nauseosus* (rubber rabbitbrush), and *Cercocarpus ledifolius* and *C. montanus* (curl-leaf and alder leaf mountain mohagany).

LOWDER CREEK BOG

Lowder Creek Bog occurs in T36S, R8 1/2W, Sec. 19, Iron County, on the Dixie National Forest. Elevation of the bog is ca. 3159 m, with a surface area of ca. 3.5 ha. The bog is located ca. 3.7 km east-southeast of Brian Head, the highest peak within the vicinity (Fig. 1). The Lowder Creek Bog sediments accumulated behind a well-developed moraine complex deposited during the Late Wisconsin. The Lowder Creek Glacier (Mulvey et al., 1984) originated east of the Brian Head-Sidney Peaks crest, terminating 3.9 km to ca. 3080 m elevation.

Modern vegetation surrounding the site is *Picea engelmannii–Abies lasiocarpa* forest. *Populus tremuloides* is a common associate; *Pinus flexilis* (limber pine) grows on slopes above the bog. Members of the Cyperaceae (sedge) family cover the bog surface; common associates include *Dodecatheon pulchellum* (shooting star), *Pedicularis groenlandica* (elephant head), and *Gentiana* sp. (gentians). Additional species are listed in Table 1.

ALPINE POND

Alpine Pond (ca. 0.2 ha) occurs in Cedar Breaks National Monument, also in Iron County in T36W, R9W, Sec. 25. Elevation of the pond is 3200 m and is ca. 5.1 km south of Brian Head. Maximum depth of Alpine Pond on the day of coring was 2.3 m. Trees grow along the shore, and many trees formerly growing around the pond have fallen into it.

Exposed around the margins of the lake are sediments of the Paleocene Claron Formation. Alpine Pond occupies a small basin formed during Holocene faulting along the edge of the "Breaks." The "Breaks" are formed by erosion of the Claron Formation along the Hurricane Fault. Late Pleistocene glaciers probably occupied the site, originating on Brian Head to the north. A veneer of till (1.3 to 29 m thick) is exposed along the Hurricane Fault escarpment immediately west of the pond (Agenbroad et al., 1996).

The modern vegetation surrounding Alpine Pond is also *Picea engelmannii–Abies lasiocarpa* forest, with *Populus tremuloides*. Understory shrubs include *Juniperus communis* and *Ribes montigenum* (Table 1).

Methods

Sediment cores from Alpine Pond and Lowder Creek Bog were collected in June and September 1992, respectively. For Alpine Pond, multiple overlapping cores were taken from different locations within the pond. Only short core 11 and long core 12 are reported here. Core 11 was collected in 215 cm of water, and included 84 cm of sediment with an undisturbed sediment-mudwater interface. An adjacent, overlapping core (12) was taken in 225 cm of water with a square-rod, modified Livingstone piston corer, consisting of 313 cm of sediment. Two modified Livingstone cores were extracted from Lowder Creek Bog, with the longest totaling 727 cm of sediment. The cores were sampled for pollen, plant macrofossils, and radiocarbon dating at the Laboratory of Paleoecology (LOP) at Northern Arizona University. As an aid in interpretion of the fossil pollen modern moss polster pollen samples were taken at varying elevations near the two sites. The transect began near Parowan,

TABLE 1

Plants growing on and adjacent to Alpine Pond (19 June 1992) and Lowder Creek Bog (12 September 1992), Utah

Species		Alpine Pond	Lowder Creek Bog
Trees			
Picea engelmannii	Engelmann spruce	X	X
Abies lasiocarpa	subalpine fir	X	X
Populus tremuloides	quaking aspen	X	X
Shrubs			
Juniperus communis	common juniper	X	X
Potentilla sp.	cinquefoil	X	
Ribes sp.	currant	X	
Ribes montigenum	gooseberry currant		X
Rubus idaeus	raspberry	X	
Salix sp.	willow	X	X
Herbs			
Achillea millefolium	milfoil yarrow	X	
Agoseris sp.	agoseris	X	
Agoseris glauca	pale agoseris		X
Antennaria sp.	pussytoes	X	X
Aster occidentalis	western aster	X	
Aster foliaceus	leafybract aster	X	
Bromus vulgaris	Columbia brome	X	
Caltha leptosepala	marsh marigold	X	X
Castilleja miniata	scarlet paintbrush	X	X
Cirsium sp.	thistle		X
Cirsium cf. *neomexicana*	New Mexico thistle	X	
Delphinium cf. *barbeyi*	western larkspur		X
Dodecatheon pulchellum	shooting star	X	
Fragaria sp.	strawberry	X	
Fragaria virginiana	mountain strawberry		X
Gentianopsis detonsa	meadow gentian	X	
Lupinus sp.	lupine		X
Lupinus cf. *argenteus*	silvery lupine	X	
Mertensia ciliata	mountain bluebell		X
Pedicularis groenlandica	elephant head	X	
Phleum pratense	timothy grass	X	
Poa pratensis	Kentucky bluegrass	X	
Polemonium sp.	jacobsladder	X	
Polemonium pulcherrimum	pretty jacobsladder		X
Primula parryi	Parry primrose		X
Ranunculus eschscholtzii	Eschscholtz buttercup		X
Rorippa sp.	cress	X	
Rumex sp.	dock	X	
Sitanion sp.	squirrel tail	X	
Smilicina stellata	smilacina		X
Solidago multiradiata	low goldenrod	X	
Stipa spp. (2 species)	needlegrass	X	
Swertia radiata	deer's tongue	X	X
Thlaspi montanum	thlaspi		X
Thalictrum fendleri	Fendler meadowrue	X	X
Trisetum spicatum	spike trisetum	X	
Viola nephrophylla	bog violet	X	

Utah, continued south along State Hwy. 143 to Cedar Breaks, and ended near Long Valley Junction (Fig. 1).

Fossil pollen samples (1 cm^3) were taken at 15- to 25-cm (usually 20 cm) intervals along the length of the core. We followed a modified Faegri and Iversen (1989) process, which included suspension in KOH, then dilute HCl, HF and acetolysis solution. A known amount of *Lycopodium* spores were added for calculation of pollen concentration. Additionally, some samples from lower levels in the Lowder Creek Bog core containing high silt and clay were sieved (7 μm mesh; Cwynar et al., 1979). The modern pollen samples were processed in a similar manner.

Pollen identifications were made using reference material and published keys (Kapp, 1969; Moore et al., 1991) at the LOP. Pollen slides were scanned at 400×, to a minimum pollen sum of 300 grains. The pollen sum consisted of all terrestrial pollen types, and excluded wetland and aquatic pollen (mostly Cyperaceae and *Polygonum bistorta*), and spores (*Pediastrum*). Pollen zones were defined by visual inspection. The complete pollen data are deposited in the North American Database available from the World Data Center-A for Paleoclimatology, *www.ngdc.noaa.gov/paleo/pollen.html.*

Where possible, *Pinus* grains were subdivided into subge-

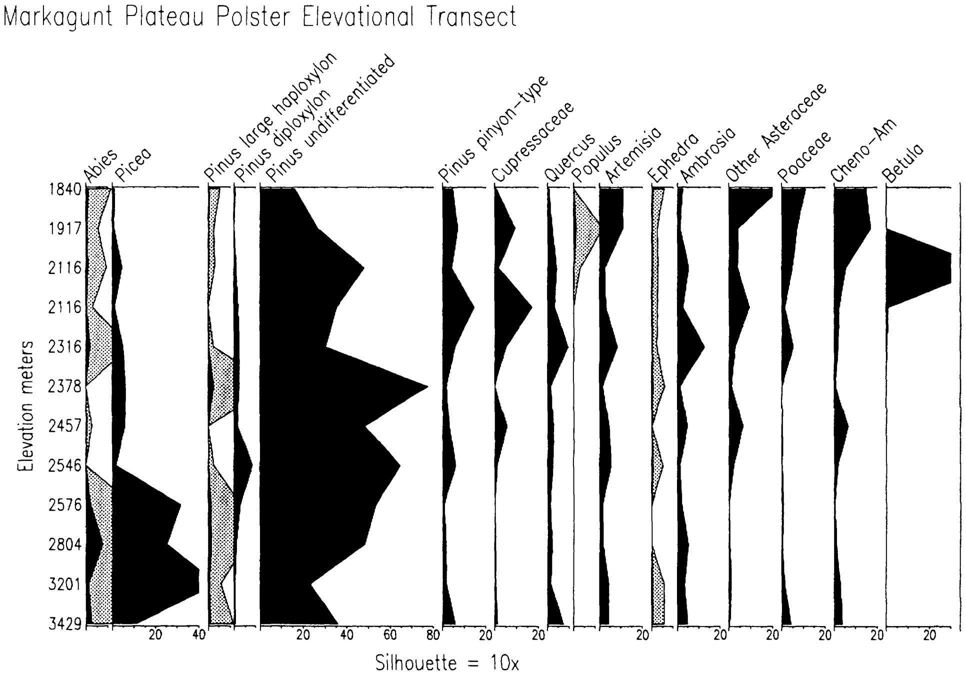

FIGURE 3. Modern pollen from moss polsters, collected from a transect of elevations on the Markagunt Plateau. Elevations and modern vegetation of polster sites are described in Table 2.

neric categories (Jacobs, 1985). Piñon-type pine (*P. edulis* and *P. monophylla* of lower elevation woodlands today) included *Pinus* subgenus *strobus* grains with verrucae on the leptoma and were <70 μm in total length. Larger (>70 μm) grains in this group, predominantly from high-elevation white pines, were distinguished from *Pinus* subgenus *pinus* grains (without verrucae on the leptoma).

Macrofossil samples from Lowder Creek Bog and Alpine Pond (core 12 only) were sieved from ca. 100 cm^3 of sediment through 850 μm (core 20) and 180 μm (core 80) mesh soil sieves. These were then sorted and identified by comparison to the reference collection at the LOP. Needle fragments were identified according to external and internal morphology, as in Anderson (1993). *Abies* needles differ with respect to the placement of the resin canals within the needle. In *A. lasiocarpa* the resin canals are lateral within the parenchyma (Durrell, 1916). For *Picea* needles, identification is based upon characteristics of the leaf tip (blunt in *P. engelmannii,* sharp in *P. pungens,* the size of the resin ducts (larger in *P. engelmannii*), and the absence (*P. engelmannii*) or presence (*P. pungens*) of a separation within the vascular bundle (Durrell, 1916). Identification in *Pinus* is based upon the number of fibrovascular bundles in the needle (one or two), the exterior shape of the needle in cross-section (triangular, circular, or semicircular), and the placement of the resin canals (Harlow, 1947). Needles were tallied as total length of whole and broken fragments for each species and reported as numbers per 100 cm^3.

Results

MODERN POLLEN RAIN

The use of modern pollen assemblages from moss polsters to interpret fossil pollen sequences is controversial. Fall (1992) noted minimal difference between pollen influx to small lakes and atmospheric collectors in subalpine and alpine vegetation types. However, Dunwiddie (1987) found significant discrepancies in a comparison of modern moss polsters and modern coretop pollen assemblages. Jackson and Wong (1994) found that 25 to 90% of pollen found in moss polsters was from trees outside their 20-m sampling radius. We use caution in our interpretations of fossil pollen but note that significant changes in pollen assemblages occur in our modern samples over the elevational gradient. Therefore, moss polster pollen data can be important at elevations where lakes are rare or absent.

Twelve modern pollen samples were collected from a transect of sites (1840 to 3429 m elevation) near Lowder Creek Bog and Alpine Pond (Fig. 3; Table 2). Vegetation along this portion of the transect varies from an open scrub dominated by *Artemisia,* Asteraceae, and Poaceae at the lowest elevations, to semiclosed forest at the upper end. *Pinus edulis* is found at all locations up to 2316 m, with *Juniperus osteosperma* also dominating these elevations. *Quercus gambellii* (Gambel oak) becomes important above 2116 m, and oak, *Abies concolor,* and *Pseudotsuga menziesii* largely replace *J. osteosperma* at 2316 m elevation.

Pollen assemblages from elevations up to 2316 m are characterized by the highest percentages of nonarboreal types, including Poaceae, Chenopodiaceae, *Artemisia,* Asteraceae, and *Ambrosia* (ragweed). Cupressaceae and *P. edulis*-type pollen are also most abundant below 2316 m. Undifferentiated *Pinus* pollen is generally 20 to 40% of the sum, while pollen of subalpine conifers (*Abies,* below 2%; *Picea* below 8%) is at lowest values in the transect.

Open woodland and closed mixed-conifer forest dominates the vegetation between 2316 and 2576 m elevation. *Pinus ponderosa* dominates the lower portion of this segment, with codominant *Pseudotsuga menziesii, Abies concolor, Pinus flexilis,* and *Juniperus osteosperma.* At the upper end of this segment, *Populus tremuloides* and *Pseudotsuga menziesii* dominate, with codominants *Pinus flexilis* and *P. ponderosa. Juniperus communis* becomes abundant in the understory. *Pinus* pollen reaches its maximum percentage (ca. 50 and 80%) over this stretch of the transect. *Pinus ponderosa*–type pine pollen reaches a high of 8% at the 2546 m elevation site. *Picea* pollen becomes abun-

TABLE 2

Dominant vegetation at moss polster locations, Markagunt Plateau, Utah. See Figure 1 for locations of moss polsters

Polster	Elevation (m)	Dominant vegetation
1	1840	Open Scrub. *Artemisia tridentata, Chrysothamnus nauseosus, Salsola kali,* herbaceous Asteraceae, Poaceae.
2	1917	Open woodland. *Juniperus osteosperma, Pinus edulis, Populus fremontii, P. angustifolia, Artemisia tridentata, Chrysothamnus nauseosus, Salsola* sp., *Aster* sp.
3	2116	Closed riparian. *Populus angustifolia, Rhus trilobata, Acer glabrum, Rosa woodsii, Salix* sp.
4	2116	Open, dry slope. *Pinus edulis, Juniperus osteosperma, Quercus gambelii, Rhus trilobata, Artemisia* sp., *Chrysothamnus nauseosus, Opuntia basilaris.*
5	2316	Semi-closed vegetation. *Quercus gambelii, Abies concolor, Betula occidentalis, Pinus edulis, Pseudotsuga menziesii.*
6	2378	Closed forest. *Pinus ponderosa, Pseudotsuga menziesii, Abies concolor, Pinus flexilis, Juniperus osteosperma, Purshia neomexicana, Berberis repens, Arctostaphylos* sp., *Prunus* sp., *Verbascum thapsis,* Poaceae, Asteraceae.
7	2457	Open woodland. *Pinus ponderosa, P. flexilis, Pseudotsuga menziesii, Abies concolor, Populus tremuloides, Arctostaphylos* sp.
8	2546	Closed forest. *Populus tremuloides, Pinus ponderosa, Abies concolor, Juniperus osteosperma,* Poaceae.
9	2576	Open woodland. *Pseudotsuga menziesii, Populus tremuloides, Pinus flexilis, P. ponderosa, Juniperus communis, Chrysothamnus* sp., Poaceae.
10	2804	Closed forest. *Pinus flexilis, Abies* sp., *Juniperus communis, Populus tremuloides, Pseudotsuga menziesii,* Poaceae.
11	3201	Closed forest. *Picea engelmannii, Abies lasiocarpa, Juniperus communis, Populus tremuloides, Ribes montigenum.*
12	3429	Open tundra. *Phlox* sp., *Antennaria alpina, Eriogonum ovatifolium, Swertia* sp., *Trisetum spicatum, Muhlenbergia* sp., *Lotus* sp., *Ribes montigenum.*

dant at the highest site in the segment, although *Picea* trees are absent.

Closed forest conditions are found above 2576 m elevation, with *Pinus flexilis* and *Abies* dominating the vegetation at 2804 m, and *Picea engelmannii* and *A. lasiocarpa* at 3201 m. *Picea* pollen dominates the assemblages at sites between 2576 and 3201 m elevation (ca. 25–<40%). *Abies* pollen also reaches a maximum of 8% at 2804 m. At the highest elevation site in alpine tundra (3429 m), *Picea* pollen declines, and pollen of nonarboreal plants rises slightly.

CORE CHRONOLOGIES

Four bulk sediment samples consisting of half-core segments of 6 to 17 cm length were dated from the Lowder Creek Bog core (Table 3). Sedimentation has been essentially constant throughout the time of deposition (Fig. 4) with interpolated sediment accumulation rates varying from 0.047 to 0.065 cm yr^{-1}.

Bulk sediment dating could not be used for Alpine Pond sediments, which are slightly calcareous. Instead, spruce wood extracted from the sediment matrix was dated (Table 3). Average sediment accumulation rate for most of the core is 0.098 cm yr^{-1} (Fig. 4).

TABLE 3

Radiocarbon dates for the Lowder Creek Bog and Alpine Pond cores

Core	Depth (cm)	Laboratory no.	Age (yr BP)
Lowder Creek Bog 1			
	147–153	Beta-93033	2700 ± 70
	322–328	Beta-93034	6410 ± 110
	500–512	Beta-59897	9200 ± 100
	704–721	Beta-56945	13020 ± 690
Alpine Pond			
12	258–262	Beta-54270	2640 ± 130

CORE LITHOLOGIES

The 723-cm Lowder Creek Bog core consists of coarse to medium sedge peat from the bog surface to ca. 475 cm depth (Figs. 5, 6), with increasing humification toward the bottom of this section. Peaty lake sediments are found from 475 cm to ca. 527 cm. Clayey lake sediments, with some sections distinctly laminated, occur below 527 cm. A volcanic tephra occurs at ca. 643 cm.

A composite stratigraphy of cores 11 and 12 constitute a 313-cm record from Alpine Pond. Sediments consist of massive (some laminated) organic-rich lake lake muds (Fig. 8). Light to dark olive brown gyttja with locally abundant plant macrofossils occurs from the surface to ca. 225 cm. Laminated, light tan lake clays are found from 225 to 250 cm. Below 250 cm laminations give way to massively-bedded silts and clays; a coarse macrofossil layer occurs from 271 to 279 cm.

LOWDER CREEK BOG FOSSIL POLLEN AND MACROFOSSILS

Pollen Zone I (ca. 13,000 to 9800 yr BP)

Artemisia dominates both the pollen percentage and influx diagrams, with smaller amounts of *Juniperus* (perhaps *J. communis*) and Other Asteraceae (Figs. 5 and 6). The generally low percentages (below 10%) and influx of *Picea* and *Abies* (below 1% and 50 grains/cm^2/yr), as well as the absence of their macrofossils (Fig. 7), suggests these conifers were either absent or very rare within the local vicinity. *Pediastrum* (Figs. 5 and 6) and aquatic insects and zooplankters (Fig. 7) suggest a lacustrine origin of the sediment.

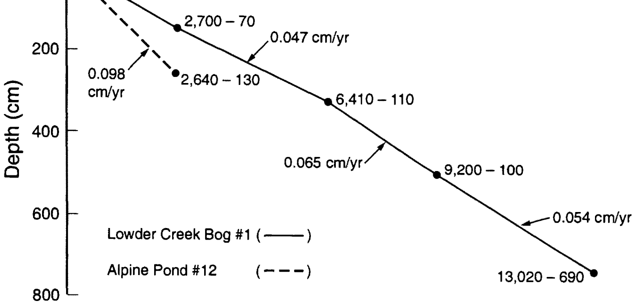

FIGURE 4. Radiocarbon ages and sediment accumulation rates for Lowder Creek Bog core 1 and Alpine Pond core 12.

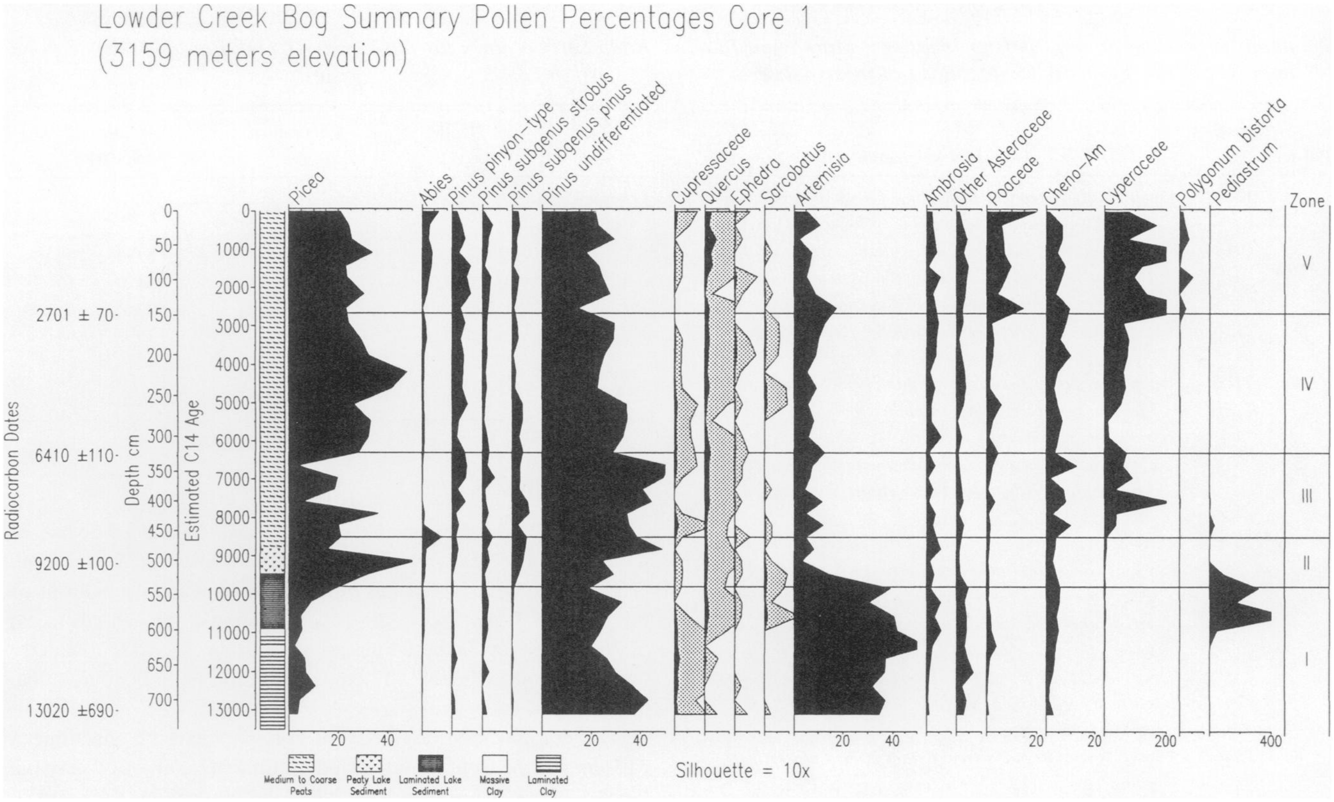

FIGURE 5. Summary pollen percentage data from Lowder Creek Bog core 1. Note change in scales for aquatics.

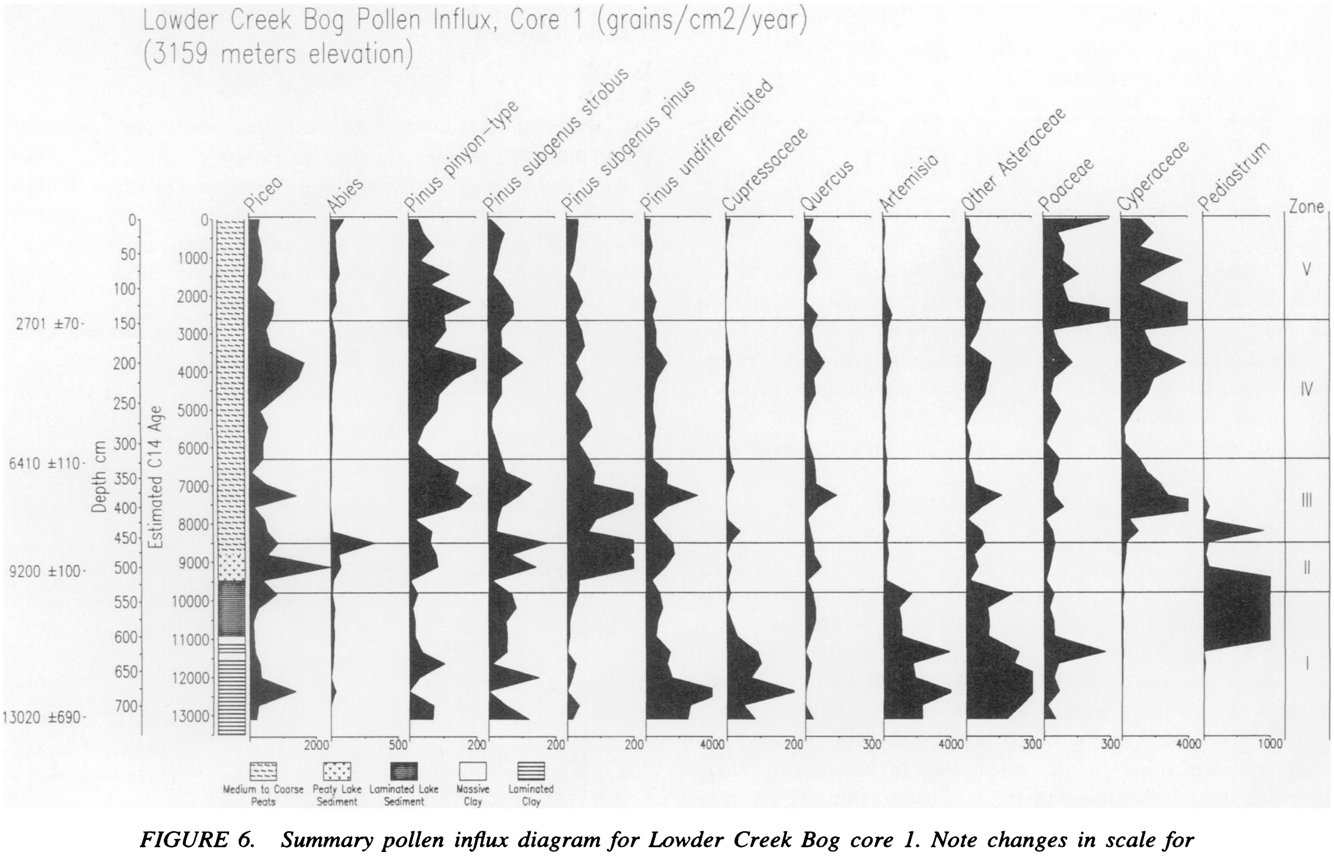

FIGURE 6. Summary pollen influx diagram for Lowder Creek Bog core 1. Note changes in scale for the various pollen types.

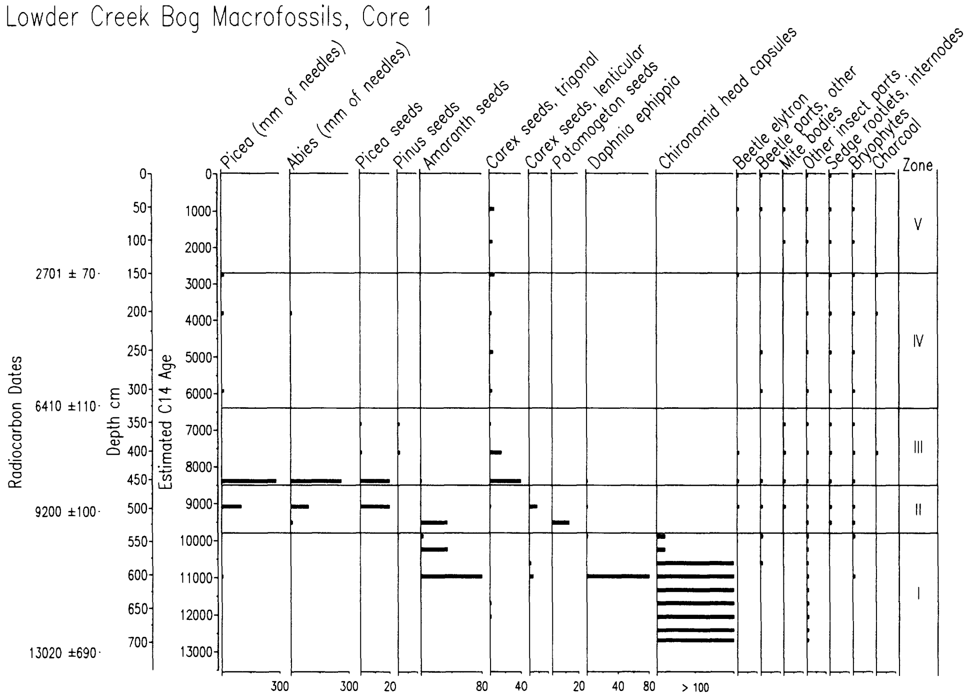

FIGURE 7. Summary plant macrofossil data from Lowder Creek Bog core 1. Note variable scales. Numbers / 100 cm^3.

Pollen Zone II (ca. 9800 to ca. 8500 yr BP)

Picea pollen percentages and influxes increase briefly, then decline, followed by a similar sequence for *Abies.* Maximum macrofossil concentrations indicate local occurrence of these trees (Fig. 7). Nonarboreal and *Juniperus* pollen declines, while *Pinus* subgenus *pinus* (probably ponderosa pine) pollen influx begins an increase that lasts into the next zone. Biologic indicators of permanent water, such as *Pediastrum,* chironomids and *Daphnia,* disappear from the macrofossil record.

Pollen Zone III (ca. 8500 to ca. 6400 yr BP)

Picea declines to its lowest Holocene percentages during this zone, varying from ca. 5 to 20% (one sample attains 35%), with only minimal decline in influx. *Abies* also declines, but percentages and influx of all *Pinus* pollen types remain high, including the lower-elevation piñon pine-type. Undifferentiated *Pinus* reaches a Holocene maximum, while *Pinus* subgenus *pinus* declines somewhat after ca. 7000 yr BP. An increase in pollen and fruits of Cyperaceae as well as sedimentary change to coarse sedge peat indicate the first development of a true sedge bog.

Pollen Zone IV (ca. 6400 to ca. 2700 yr BP)

Picea pollen percentages recover to 24 to 48%, although influx values do not rise until ca. 4800 yr BP. Undifferentiated *Pinus* pollen declines to 24 to 33%, and *Pinus* subgenus *pinus* percentages decline again after ca. 4800 yr BP. *Artemisia* pollen increases near the end of the zone. *Quercus* and nonarboreal (*Ambrosia,* Poaceae, and Cheno-am) pollen types remain unchanged.

Pollen Zone V (ca. 2700 yr BP to present)

The most significant pollen changes in this zone occur in the nonarboreal types, with increases in Cyperaceae, Poaceae, and *Polygonum bistorta. Abies* pollen also increases throughout the zone, while *Picea* pollen percentages and influx decline somewhat. Other pollen types remain largely unchanged from pollen zone IV. No macrofossils of terrestrial plants were recovered.

ALPINE POND FOSSIL POLLEN AND MACROFOSSILS

Since the Alpine Pond record covers only the last ca. 3000 yr, most of the record is contemporaneous with Pollen Zone V at Lowder Creek Bog (Fig. 8). However, the bottom three samples are placed in Pollen Zone IV. These samples differ from the upper record by somewhat higher percentages of *Picea* pollen, and lower percentages of *Abies* and Cyperaceae pollen.

Pollen Zone V (ca. 2700 yr BP to present)

Picea pollen and macrofossils dominate the pollen and macrofossil assemblages, while *Abies* pollen percentages increase after ca. 2700 yr BP; *A. lasiocarpa* macrofossils are abundant throughout the zone (Fig. 8). Cyperaceae and Poaceae pollen also increases, although percentages are lower than in comparable levels at Lowder Creek Bog. *Artemisia* declines consistently over the last ca. 500 yr. Most additional pollen types remain relatively consistent throughout the zone.

Discussion

VEGETATION HISTORY OF THE SUBALPINE MARKAGUNT AND SOUTHERN COLORADO PLATEAUS

Late Wisconsin

During the late Wisconsin, plateau and mountain glaciers covered much of the highest elevations of the southern Colorado Plateau, including the Aquarius, Fish Lake, Thousand Lake Plateaus (Flint and Denny, 1958) and LaSal Mountains (Richmond, 1962) of Utah, and the San Francisco Peaks and White Moun-

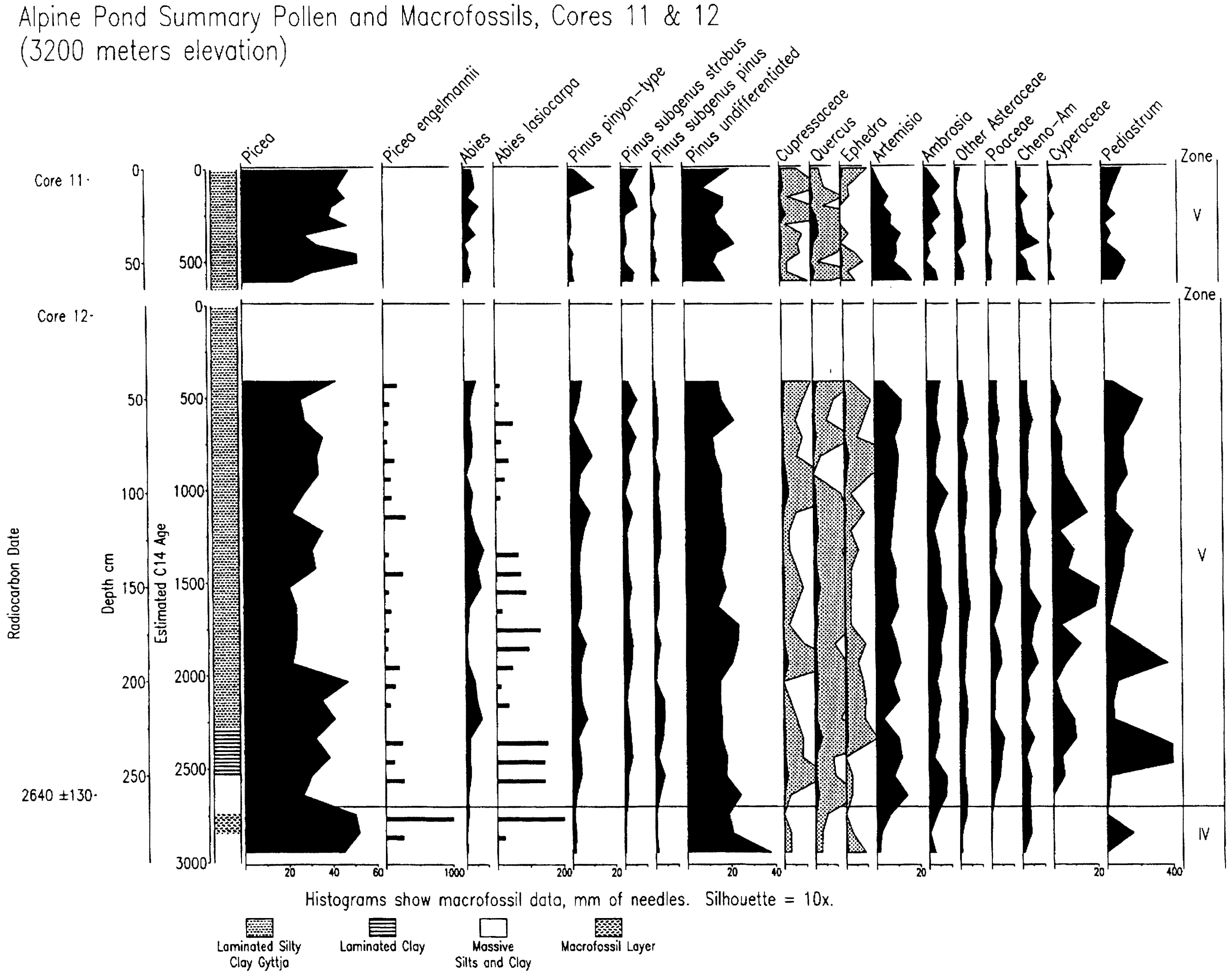

FIGURE 8. Summary pollen percentage and plant macrofossil data from Alpine Pond cores 11 (upper portion of diagram) and 12 (lower portion of diagram). Macrofossils were analyzed only for core 12.

tains of Arizona (Péwé and Updike, 1975; Merrill and Péwé, 1977). Elevational ranges of individual plant species were depressed as much as 700 to 800 m in the Great Basin (Thompson, 1990; Rhode and Madsen, 1995), 720 to 800 m in the Grand Canyon (Phillips, 1977; Cole, 1990), 570 to 800 m along the Mogollon Rim of the southern Colorado Plateau (Jacobs, 1983; Anderson, 1993; Anderson et al., 1999), and at least 300 to 700 m lower in west-central Colorado (Fall, 1997). Lower elevation sites across the Colorado Plateau show similar elevational displacements (Betancourt, 1990; Anderson et al., 1999).

The deglacial sequence of the high plateaus is poorly dated at present, but deglaciation in the Wasatch Mountains of north-central Utah occurred by 12,300 ± 330 yr BP (Madsen and Currey, 1979) and by ca. 13,000 yr ago in the Lowder Creek Bog area. During and subsequent to deglaciation subalpine tree species such as *Picea engelmannii* and *Abies lasiocarpa* were probably rare or absent at this elevation near Lowder Creek Bog. *Artemisia* (sagebrush) was probably abundant in this treeless environment. Alternatively, the locally-open vegetation could have allowed greater deposition of pollen from *Artemisia* growing in the valley bottoms below the site. Packrat middens found in the Great Basin west of Lowder Creek Bog are dominated by *Artemisia,* as well as other species (Thompson, 1990; Rhode and Madsen, 1995). Late Pleistocene pollen spectra from both marsh (Thompson, 1992) and pluvial lake (Spencer et al., 1984; Davis, 1998; Davis and Moutoux, 1998) sediments are also dominated by *Artemisia* pollen. Similarly, high *Pinus* percentages and influx suggests pines either grew at the site, or were abundant at lower elevations.

Picea engelmannii grew near the site by at least 11,000 yr BP (Fig. 7). To the north, *Picea* had become established at the recently deglaciated Huntington Reservoir Site by 11,500 yr BP (2740 m; Gillette and Madsen, 1993) and at Snowbird Bog by 12,300 yr BP (2450 m; Madsen and Currey, 1979). On the eastern edge of the Colorado Plateau, *Picea* dominated at the Dome Creek Meadow site (3765 m; Feiler et al., 1997), as well as at subalpine sites in west-central Colorado (Fall, 1997). To the south on the Kaibab Plateau, *P. engelmannii* replaced alpine parkland by ca. 11,000 yr BP at Fracas Lake (2518 m), and Bear Lake (2778 m) (Weng and Jackson, 1999). Farther south at Potato Lake, Arizona, (2222 m; Anderson, 1993), *P. englemannii* dominated conifer forests there throughout the late Wisconsin.

Early Holocene

Pollen evidence suggests that *P. engelmannii* and *Abies lasiocarpa* had become well-established around the Lowder Creek Bog site by ca. 9800 yr ago. At lower elevation sites on the southern Colorado Plateau subalpine conifers were replaced by *Pinus ponderosa* forest by ca. 10,400 yr BP at Potato Lake (Anderson, 1993) and by ca. 9800 yr BP at Fracas Lake. *Pinus ponderosa* was established at Bear Lake after 8800 yr BP (Weng and Jackson, 1999). A substantial increase in *P. ponderosa* influx at 9500 yr BP at Lowder Creek Bog provides confirmation of widespread establishment.

Picea may have been somewhat less abundant around Lowder Creek Bog by ca. 8500 yr BP as the small pond developed into a fen or mire. Biologic indicators of permanent water, such as *Pediastrum,* disappear from the record. Whether this conversion was completely climate-driven is uncertain. Sedimentologic evidence from Fracas and Bear Lakes suggest wettest conditions of the Holocene there occurred from ca. 10,000 to 8000 yr BP with the greatest development of the southwestern monsoon (Weng and Jackson, 1999). However, the timing at Lowder Creek Bog is most similar to the Stoneman Lake record (Hasbargen, 1994) which shows a transition from high to lower lake levels by ca. 8500 yr BP.

Data from eight sites in west-central Colorado (Fall, 1997) suggest initiation of monsoonal conditions by about 9000 yr ago. There, subalpine forest occupied a wider elevational range, with upper treeline growing ca. 270 m higher, and lower treeline extending further toward the valley bottoms.

Early to Middle Holocene Transitions

The decline in *Abies* and fluctuations in *Picea, Pinus,* and other nonarboreal pollen between ca. 8500 and 6400 yr ago at Lowder Creek Bog could be a function of several factors. Seral changes within the basin may have made the local environment less favorable for *Abies* and *Picea,* although macrofossils show *Picea* trees remained locally present. Climate change provides a second potential explanation. Warming conditions of the early Holocene may have forced *Abies, Picea,* and *Pinus* locally to higher elevations, or may have resulted in a more open subalpine forest. In this scenario, Lowder Creek Bog existed near a sensitive *Picea/Pinus* ecotone, controlled by temperature. The expansion of *Pinus ponderosa* upslope, but well short of the Bog, would reduce the area occupied by *Picea* and bring dense stands of *Pinus ponderosa* closer to the site. This possibility is suggested by modern pollen studies to the south (Jackson and Smith, 1994). Alternatively, fluctuations in *Picea* and nonarboreal pollen may indicate a sensitivity to precipitation changes throughout the period.

Feiler et al. (1997) considered the decline in spruce at ca. 8100 yr BP in northwest Colorado to mark the beginning of a warm, dry period lasting into the middle Holocene. At Dome Creek Meadow plants more characteristic of open ground increased, indicating a more open forest community surrounding the site. At the Snowbird Bog site in the Wasatch Range, warmer and drier conditions also commenced beginning about 8000 yr ago (Madsen and Currey, 1979). These factors are indicative of an early mid-Holocene increase in temperature with decreased effective precipitation. Warm and wet conditions continued throughout this period at the west-central Colorado sites (Fall, 1997), where intense monsoonal precipitation may have lasted until ca. 6000 yr ago.

A third explanation involves insect infestation. Spruce bark beetle, *Dendroctonus rufipenis,* periodically infests *P. engelmannii* stands in Utah and Colorado, causing widespread mortality of *Picea* (Schmidt and Frye, 1977; Baker and Veblen, 1990; Veblen et al., 1994). Feiler et al. (1997) and Anderson (1999) both attributed drastic declines in *Picea* pollen within cores from the White River Plateau to the effects of 120 yr of bark beetle infestation within the region.

Middle Holocene

After ca. 6500 yr BP *Picea* pollen percentages increased and *Picea* pollen influx becomes more consistent, suggesting a greater dominance of *Picea* once again around Lowder Creek Bog. *Picea* remained an important conifer near the bog for the remainder of the Holocene. Weng and Jackson (1999) interpreted the middle Holocene to be the driest at both of the Kaibab Plateau sites to the south. The summer drought-tolerant *Pseudotsuga menziesii* became established around Bear Lake, and water levels declined there, by ca. 6700 yr BP; water levels declined at Fracas Lake by ca. 6000 yr BP. Lowest Holocene lake levels occurred at Stoneman Lake from ca. 8500 to 2500 yr BP (Hasbargen, 1994).

Warm and dry conditions continued at the Snowbird Bog site (Madsen and Currey, 1979), and at Dome Creek Meadow in Colorado until ca. 4600 yr BP (Feiler et al., 1997). By ca. 6000 yr BP the lower forest border retreated upslope at the west-central Colorado sites (Fall, 1997), driven by drier conditions.

Late Holocene

While *Pinus ponderosa* persisted at both Potato Lake (2222 m) and Fracas Lake (2518 m) throughout the Holocene the record from both Lowder Creek Bog (3159 m) and Bear Lake (2778 m) demonstrate the dynamics of the tree at its upper elevation extreme. Pollen of *P. ponderosa* declined between 5000 and 4500 yr ago, suggesting that populations near or below Lowder Creek Bog declined while *Picea* prospered. A nearly identical, contemporaneous decline was identified at Bear Lake, though of lesser magnitude (Weng and Jackson, 1999).

Similar, nearly synchronous, changes also appear in the more northerly records from Colorado and the Wasatch Range of Utah. At Dome Creek Meadow, the subalpine forest reverted to its early Holocene character after ca. 4600 yr BP (Feiler et al., 1997). Shrinkage of the elevational range of the subalpine forest in west-central Colorado began as early as 6000, and was completed by 4000 yr BP (Fall, 1997). The analogous shift in vegetation at the Snowbird Bog site occurred by ca. 5000 yr ago (Madsen and Currey, 1979).

Lowder Creek Bog and Alpine Pond both show an increase in *Abies,* certainly *A. lasiocarpa,* throughout the late Holocene (Figs. 5, 6, 8), also noted at the Bear Lake site (Weng and Jackson, 1999). At Lowder Creek Bog, the most significant changes appear to have been in the characteristics of the bog flora itself. Members of the Poaceae, Cyperaceae, and in particular *Polygonum bistorta* increased, suggesting increased soil moisture during the late Holocene. Along with high Cyperaceae pollen from Alpine Pond these indicators reflect a substantial increase in effective moisture by ca. 2700 yr ago. Though the timing of similar changes are a little earlier at Fracas, Bear (Weng and Jackson, 1999), and Potato (Anderson, 1993) Lakes, and a little later at Stoneman Lake (Hasbargen, 1994), higher lake levels during the late Holocene at those four sites indicate a widespread phenomenon across the southern Colorado Plateau. These changes were probably driven by cooler temperatures, as shown by conversion of krummholz to alpine tundra in west-central Colorado (Fall, 1997).

PALEOCLIMATES OF THE COLORADO PLATEAU AND NEARBY GREAT BASIN

Thompson et al. (1993) estimated annual surface temperature and other climatic factors using empirically derived boundary conditions built within a general circulation model (the Community Climate Model [CCM0]) (Kutzbach and Guetter, 1986; Kutzbach et al., 1993) for several regions in western North America. At least two major, large-scale responses to changing conditions in North America were observed: (1) atmospheric airflow patterns were strongly influenced by the position and height of the Laurentide Ice Sheet, which diverted the westerlies as much as 18 degrees latitude south of the present average position, and (2) surface temperatures were 1 to 2°C higher than present in the early Holocene due to increased summer insolation. Much of the Plateau and all of the Great Basin showed a reduced temperature of at least 3.2°C at 18,000 yr BP, ca. 3°C cooler at ca. 12,000 yr BP, essentially modern temperatures at ca. 9000 yr BP, and a ca. 0.3°C increase during the middle Holocene.

Anderson (1993) suggested the late Wisconsin of the Mogollon Rim was up to 5.8°C cooler annually than at present, but up to 7°C cooler during the summer. Using *Neotoma* fecal pellet size as a measure of body size, Smith and Betancourt (1998) inferred temperatures 6 to 9° C cooler than present at lowland sites on the southeastern Colorado Plateau during the late Wisconsin, but up to 1° C warmer than present for much of the Holocene. Paleobotanical data from packrat middens (Betancourt, 1990) agreed well with these estimates, suggesting warm season temperatures at least 6.3°C cooler during the Wisconsin. An absence of *Pinus ponderosa* from Wisconsin-age sites on the Colorado Plateau argued for reduced summer precipitation as well (Betancourt, 1990; Anderson, 1993). Similarly, packrat midden data from the eastern Great Basin implied summer temperature depression of 6 to 7°C during the terminal Wisconsin (Rhode and Madsen, 1995). Estimates derived from late-glacial alpine and montane treelines in west-central Colorado suggested temperatures were 2 to 5°C cooler, and 1 to 2°C warmer than present during the middle Holocene (Fall, 1997).

Although we did not derive specific temperature or precipitation estimates for the Lowder Creek Bog data, the pollen sequence supports an interpretation of greater effective precipitation during the early Holocene, followed by warmer temperatures and variable precipitation after ca. 8500 yr BP, continuing into the middle Holocene. The sequence from Lowder Creek Bog and at other sites on the western Colorado Plateau (e.g., Weng and Jackson, 1999) is similar to that from northwestern Colorado, where the maximum influence of monsoon activity may have waned by the end of the early Holocene. Feiler et al. (1997) suggested that the difference between the records of northwest and west-central Colorado was due to a precipitation boundary running southwest to northeast through central Colorado (Mitchell, 1976), south of the White River Plateau. Markgraf and Scott (1981) originally suggested a northward shift of this boundary during the middle Holocene which may account for elevated precipitation within central Colorado. Alternatively, the variation in length of maximum monsoonal influence may be due to site sensitivity.

Declines in summer insolation (Kutzbach and Guetter, 1986; Kutzbach et al., 1993) contributed substantially to Late Holocene cooling, with declining temperatures and increasing effective precipitation at most sites, including Lowder Creek Bog, within the region. This is demonstrated by contracting treelines in Colorado by ca. 4000 yr BP, higher water water levels at Bear Lake by ca. 3800 yr BP, Potato Lake by ca. 3000 yr BP, Stoneman Lake by ca. 2500 yr BP, by ca. 2100 yr BP at Fracas Lake, and increased soil moisture at Lowder Creek Bog by ca. 2700 yr BP (Anderson, 1993; Hasbargen, 1994; Fall, 1997; Feiler et al., 1997; Weng and Jackson, 1999).

Summary and Conclusions

The 13,000-yr combined record from Lowder Creek Bog and Alpine Pond are the first to be published from the Markagunt Plateau, and show an early colonization by plants of formerly glaciated uplands on the Colorado Plateau. The Late Wisconsin vegetation may have been analogous to a *Picea* parkland, with few *Picea* trees but abundant *Artemisia. Picea* and *Abies* surrounded the site during the early Holocene to ca. 8500 yr BP, but subsequently subalpine trees were of somewhat diminished presence in the local vegetation. We advanced three different explanations for this phenomenon, including periodic thinning of the forests or upslope dispersal of *Picea* resulting from warming climates, local hydrologic changes, or periodic infestation by forest pests. At the present time, we cannot conclusively distinguish between these hypotheses. The middle Holocene was certainly the warmest portion of the postglacial there. Variable precipitation is indicated by fluctuations in the influx of *Picea and Pinus ponderosa.* The subsequent stabilization and increase in *Picea* and *Abies* demonstrated that the modern subalpine forest assemblage at these sites was established during the late-middle Holocene, with only minor changes in the local environment during the late Holocene.

The records from the Markagunt Plateau also illuminate information about the paleoclimates of the latest Quaternary. Located on the western flank of the Colorado Plateau, these sites have produced records similar to others on the Kaibab Plateau (Weng and Jackson, 1999) and Mogollon Rim (Anderson, 1993) to the south, and in northwestern Colorado (Feiler et al., 1997). The cold, moist conditions of the late Wisconsin were succeeded by the warmer, moist climates of the early Holocene. During the middle Holocene warm and/or dry climates prevailed. In west-central Colorado (Fall, 1997) a similar regime dominated, but early Holocene moist conditions may have lingered into the middle Holocene. These observations may be related to the history of the Arizona Monsoon, and the spatial pattern of this shift in precipitation regimes should be investigated in greater detail.

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