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Late Glacial and Holocene vegetation history and paleoclimate of the Kaibab Plateau, Arizona

Chengyu Weng [*], Stephen T. Jackson

Department of Botany, University of Wyoming, Laramie, WY 82070, USA

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Abstract

Sediment cores spanning the last 13,500 calendar years (cal yr) were obtained from two lakes (Fracas Lake, 2518 m; Bear Lake, 2778 m) on the Kaibab Plateau in northern Arizona. Pollen and plant macrofossil records indicate that before ~12,900 cal yr B.P., high elevation landscapes of the Kaibab Plateau near Bear Lake were covered by alpine tundra, while lower elevations near Fracas Lake were occupied by *Picea* woodland. At ~12,900 cal yr B.P., *Picea engelmannii* and *Abies lasiocarpa* forest expanded upward to occupy the top of the plateau. *Pinus ponderosa* arrived near Fracas Lake 11,000 cal yr B.P., replacing *Picea* forests. Since then, *Pinus ponderosa* forest has dominated the Fracas Lake area. *Pinus ponderosa* did not appear at Bear Lake until ~9730 cal yr B.P. Mixed forests of *Picea* (mainly *Picea pungens*), *Abies lasiocarpa, Pinus ponderosa*, and *Pseudotsuga* (after ~8000 cal yr B.P.) grew near Bear Lake for the remainder of the Holocene. *Picea engelmannii* populations reexpanded near Bear Lake after 4000 cal yr B.P. Charcoal records indicate that fire probably helped *Pinus ponderosa* to become established near Bear Lake. Climate changes on the Kaibab Plateau since the Late Glacial were inferred from lake levels and vegetation patterns. The Late Glacial (>11,000 cal yr B.P.) was cold and probably wet. The early Holocene (11,000 to ~8000 cal yr B.P.) was cooler than today and may have been the wettest period. Fracas Lake and Bear Lake were probably deepest then. During this period, a strengthened summer monsoon brought in more moisture from the eastern Pacific Ocean and the Gulf of Mexico. During the dry and warm mid-Holocene, Fracas Lake and Bear Lake experienced water-level declines. The late Holocene was relatively wet and cool again, and aquatic plants were abundant in the two lakes. Increasing effective moisture in the late Holocene was related to decreasing summer insolation. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: Late Glacial; Holocene; paleoecology; vegetation change; paleoclimate; Colorado Plateau; palynology; Arizona

1. Introduction

The southwestern United States is topographically diverse. The Sierra Nevada Range of California separates coastal from interior regions. In the interior, the elevational contrast is dramatic between the southern and northern parts. The southern part of the region (south of 35°N) is dominated by low-elevation basin and range, while the northern part is occupied by high-elevation plateaus and basins, which comprise the Colorado Plateau.

Summer climates are controlled by the Subtropical High in the northeastern Pacific Ocean and the summer Southwest Monsoon from the Pacific Ocean and Gulf of Mexico (Bryson and Hare, 1974;

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[*] Corresponding author. Fax: +1-307-7662851; E-mail: weng@uwyo.edu

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Mitchell, 1976; Mock, 1996; Adams and Comrie, 1997; Higgins et al., 1997). Because of the Subtropical High, coastal California, the Sierra Nevada and the Great Basin receive little summer precipitation. The Southwest Monsoon brings precipitation to western Texas, New Mexico, Arizona and Colorado in summer. Storms brought in by the Jet Stream from the northeastern Pacific Ocean dominate winter precipitation. Latitudinal variation of the Jet Stream influences winter precipitation in the region (Bryson and Hare, 1974). The high-elevation regions, such as the Sierra Nevada Range and northern high plateaus, act as barriers to movement of air masses. Generally, the western part of the southwestern United States (coastal and Great Basin) receives mainly winter and spring precipitation originating in the Pacific Ocean, the middle part (Colorado Plateau, southern Arizona and New Mexico) has a biseasonal precipitation regime, and summer precipitation dominates in the eastern part (eastern Arizona and western New Mexico) (Sellers and Hill, 1974; Mock, 1996).

The high plateaus of the Colorado Plateau generally receive more annual precipitation than the Basin and Range owing to higher average elevation. During the late Quaternary, Milankovitch-induced insolation changes may have altered monsoonal flow and shifted the position of the Westerlies, changing the climatic patterns in this region. In particular, monsoonal precipitation may have been amplified during the early Holocene (Thompson et al., 1993). Plant distributions and lake levels are likely to have been sensitive to these climatic changes (Kutzbach and Guetter, 1986; COHMAP, 1988). This hypothesis can be tested by paleoecological reconstructions. Most previous research in this region has come from plant macrofossil analysis of packrat (*Neotoma*) middens (Betancourt, 1990; Cole, 1990; Thompson et al., 1993). However, large chronologic gaps in most packrat midden records prevent detailed reconstruction of the vegetation and climatic history. Pollen, diatom and macrofossil analyses from lake and wetland sediments can provide higher-resolution records (Whiteside, 1965; Shafer, 1989; Davis and Shafer, 1992; Thompson et al., 1993; Anderson, 1993; Blinn et al., 1994; Hasbargen, 1994). However, a hiatus during the early to mid-Holocene occurs at some sites (Hevly, 1985; Anderson, 1993), necessitating additional work for the region.

This study examines the pollen and plant macrofossil records and sediment changes in AMS-dated sediment cores from two lakes (Fracas Lake and Bear Lake) at different elevations on the Kaibab Plateau, Arizona. Objectives of the study are (1) to reveal the vegetation changes since the Late Glacial, (2) to infer the paleoclimate in the area, and (3) to relate the climate changes recorded on the Kaibab Plateau to regional changes and explore the dynamics of Holocene climate of the Colorado Plateau.

2. Study area

The Kaibab Plateau, Coconino County, Arizona, is a high plateau in the southern Colorado Plateau region of the Southwest United States (Fig. 1). The Kaibab Plateau is bounded on the south by the Grand Canyon. Elevations range from about 390 m at the bottom of the canyon to 2830 m on the top of the plateau within a 20 km distance (Fig. 1).

Vegetation of the Kaibab Plateau can be described as a series of elevational zones (Rasmussen, 1941; White and Vankat, 1993; Jackson and Smith, 1994). The landscape above 2600 m is covered with *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir) forest (Fig. 2). *Pinus ponderosa* (ponderosa pine) and *Pseudotsuga menziesii* (Douglas-fir) occur locally on ridge crests and south-facing slopes, and *Picea pungens* (Colorado blue spruce) grows locally on edges of subalpine meadows. *Populus tremuloides* (quaking aspen) is also a common element in some locations. Mixed conifer forests consisting of *Abies concolor* (white fir), *Picea pungens*, *Pseudotsuga menziesii*, *Pinus ponderosa* and *Populus tremuloides* occur between 2500 and 2700 m elevation. *Picea engelmannii* and *Abies lasiocarpa* are found locally on north-facing slopes. Forests of *Pinus ponderosa* are widespread between 2300 and 2500 m. However, this zone is extremely narrow at the eastern border (Rasmussen, 1941). *Populus tremuloides* and *Pseudotsuga menziesii* occur locally in ravines and on north-facing slopes within the ponderosa pine forest. *Pinus edulis* (Colorado pinyon), *Juniperus osteosperma* (Utah juniper) and *Quercus gambelii* (Gambel oak) are mixed with *Pinus ponderosa* at the lower portion (below 2400 m) of the zone. The vast areas with elevations be-

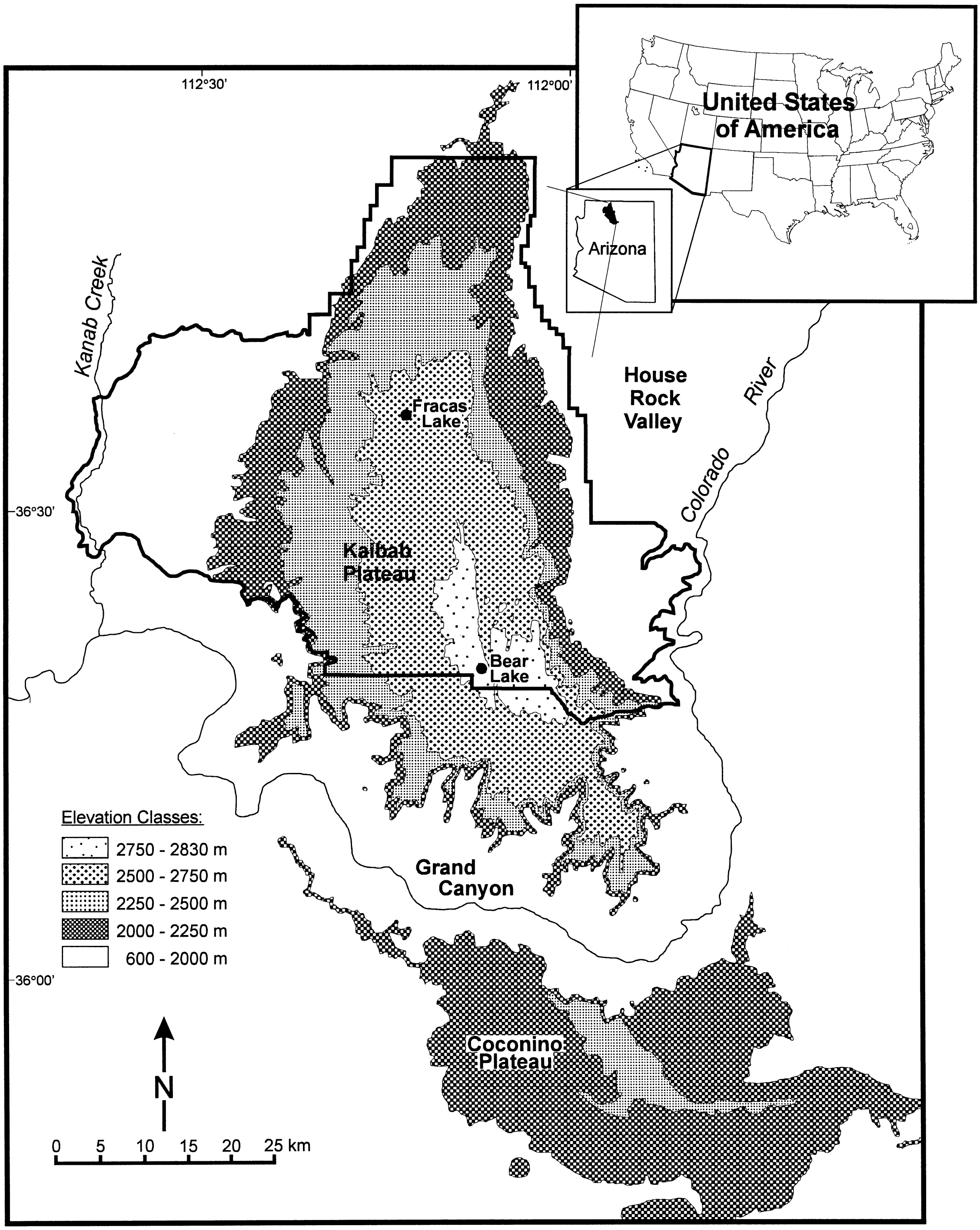


Fig. 1. Elevation map of the Kaibab Plateau and locations of the study sites. Insets show the location of the map area. The heavy black line marks the boundary of the North Kaibab Ranger District, Kaibab National Forest (modified from Jackson and Smith, 1994).

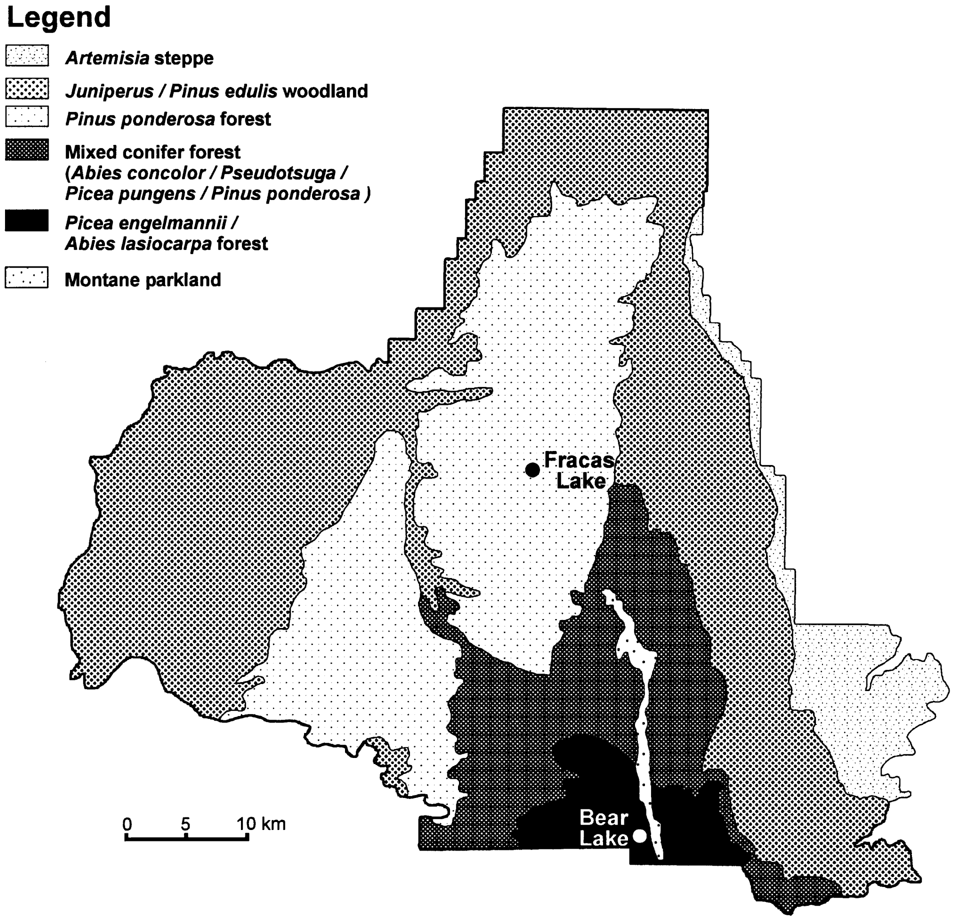


Fig. 2. Vegetation map of the North Kaibab Ranger District, Kaibab National Forest (modified from Jackson and Smith, 1994).

tween 1600 and 2300 m are occupied by *Juniperus osteosperma* and *Pinus edulis* woodland. *Juniperus monosperma* (one-seed juniper) and *Quercus gambelii* occur locally. *Artemisia* (sagebrush) steppe and desert shrubland are found below 1600 m (Fig. 2). Open mountain meadows exist throughout the plateau, especially above 2500 m.

Climate on the Plateau is characterized by biseasonal precipitation, with winter snowfall brought in by fronts from the west, and summer monsoonal rainfall coming from the eastern Pacific Ocean and the Gulf of Mexico (Sellers and Hill, 1974; Adams and Comrie, 1997; Higgins et al., 1997). Summer precipitation provides >50% of the annual moisture on the Kaibab Plateau (Mock, 1996).

3. Study sites

Fracas Lake (112°14′18″W, 36°37′20″N) is a small pond developed in a shallow sinkhole basin at an elevation of 2518 m (Fig. 1). The diameter of the basin is about 95 m (area ~0.7 ha). The pond is near the center of the basin and is only ~0.1 ha in area. Most of the basin is occupied by open meadow. Surrounding forests are composed entirely of *Pinus ponderosa* (Fig. 2). Trees occur within ca. 30–40 m of the water margin. The water depth was about one meter at the time of coring (July 1995). A sedge (*Carex*) floating mat covers about half of the water surface. *Utricularia vulgaris* (bladderwort), *Sparganium* spp. (bur reed) and *Potamogeton* spp. (pondweed) grow in the open water.

Bear Lake (112º08′48″W, 36º22′17″N, 2778 m elevation) is located about 30 km south of Fracas Lake, near the highest portion of the Kaibab Plateau (Fig. 1). Bear Lake also occurs in a sinkhole in limestone. The basin is smaller and steeper than Fracas Lake. Most of the basin is covered with water, and trees overhang the pond on all sides. Pond area is ~0.16 ha. The water was about 2 m deep at the time of coring (July 1995). A sedge (*Carex* spp., including *C. rostrata*) floating mat covers about two thirds of the water-surface. Only the surface near the east and south margin is open water. Aquatic plants in the open water area are *Glyceria borealis* (Manna grass), *Eleocharis* spp. (spike-rush), *Sparganium* spp. and *Potamogeton* spp. The surrounding forest is dominated by *Picea engelmannii* and *Abies lasiocarpa* (Fig. 2). Scattered *Abies concolor* and *Pinus ponderosa* also occur. Several *Populus tremuloides* trees grow on the west shore of the pond.

Both Fracas Lake and Bear Lake lack inlet streams and outlets. Water levels fluctuate seasonally. However, both have permanent standing water.

4. Methods

Sediment cores were taken from the centers of Bear Lake and Fracas Lake, beneath the floating mats, in July 1995, using a modified Livingstone piston corer (10-cm diameter) driven by chain hoists (Cushing and Wright, 1965).

Pollen samples 0.5 cm^3 in volume were taken at 20-cm depth intervals. Samples were taken at more frequent intervals in critical core segments. Preparation of pollen samples followed Faegri and Iversen (1989) for lake sediments, with *Lycopodium* spores as tracers for calculating pollen concentration. Preparations were mounted in silicone oil (12,500 cs) and examined at magnifications of ×400 and ×1000. Identifications of pollen were based on published atlases and keys (Kapp, 1969; McAndrews et al., 1973; Faegri and Iversen, 1989; Moore et al., 1991) and the pollen reference collection at the University of Wyoming. The species-level separation of *Pinus* pollen follows Hansen and Cushing (1973) and Jacobs (1985). Usually, at least 300 arboreal pollen grains were counted per sample. For samples near the bottom of the Bear Lake core, at least 500 terrestrial pollen grains were counted per sample.

Macrofossil samples (~70 cm^3) were obtained from the same stratigraphic levels as the pollen samples (1 cm depth span). Macrofossils were removed using 710 and 355 μm soil sieves. Macrofossils were sorted and identified under a dissecting microscope at magnifications of ×6.5 to ×40. Identifications were based on comparison with herbarium-documented reference collections.

A non-hierarchical clustering technique (optimization method) was used for zonation of pollen and macrofossil diagrams (Everitt, 1993). The minimization of within-group sum-of-squares was used as the clustering criterion. Squared Euclidean Distances were used as the measures of the distances between samples. Results were obtained by running a computer program written by one of the authors (Weng). Pollen and plant macrofossil types used for zonation are listed in Table 1.

In order to identify *Picea* to species level, *Picea* needles from selected depths were dehydrated using a graded ethanol and tertiary-butanol alcohol series, and infiltrated with melted Paraplast at 60ºC. The needles were embedded in Paraplast and continuously sectioned (15 μm thickness) using a rotary microtome. Cross-sectional anatomy was observed at ×400 magnification. Identifications were based on resin duct patterns on cross-sections of modern *Picea engelmannii* and *Picea pungens* needles. Resin ducts in *Picea engelmannii* are large (usually >200 μm; ratio of resin duct diameter to vascular bundle diameter >0.5), short (usually <3 mm) and usually below the lateral angles of needles, whereas those in *Picea pungens* are small (usually <150 μm; ratio of resin duct diameter to vascular bundle diameter <0.5), long (>3 mm) and usually at the lateral angles or slightly below the angles (Durrell, 1916; Marco, 1931; Reed and Freytag, 1949; Colleau, 1968; Weng, 1998).

Separation of fossil needles of *Abies concolor* and *Abies lasiocarpa* is based on resin-duct positions in cross-section. Fossil *Abies* needles were hand-cut using a razor blade. Resin ducts were observed under a dissecting microscope at magnification of ×40. Resin ducts are near the margins and adjacent to the abaxial epidermal layer in *Abies concolor*, but distant from margins and midway between the abaxial and adax-

Table 1
Pollen and plant macrofossil types used for zonation

Pollen or macrofossil types	Fracas Lake	Bear Lake
Pollen		
Abies	+	+
Cupressaceae	+	+
Picea	+	+
Pinus edulis	+	+
P.flexilis	+	+
P.ponderosa	+	
Pinus (total)	+	+
Pseudotsuga		+
Quercus	+	+
Ambrosia	+	+
Artemisia	+	+
Cyperaceae	+	+
Poaceae	+	+
Tubuliflorae	+	+
Rosaceae	+	+
Valerianaceae type	+	+
Caryophyllaceae		+
Chenopodiaceae/Amaranthaceae		+
Polygonum		+
Selaginella spp.		+
Macrofossils		
Picea needles	+	+
Abies needles		+
Pinus ponderosa needles	+	+
Populus scales	+	
Polygonum seeds	+	
Pseudotsuga needles		+

ial epidermal layers in *Abies lasiocarpa* (Kearney and Peebles, 1960; Flora of North America Editorial Committee, 1993). Charcoal fragments of 125–250 μm in diameter were assumed to be sensitive to local fire (Clark, 1988; Millspaugh and Whitlock, 1995; Whitlock and Millspaugh, 1996). Charcoal samples of 5 cm^3 (Fracas Lake) or 7 cm^3 (Bear Lake) from the same depth intervals as the pollen and plant macrofossil samples were sieved through 250 μm and 125 μm screens after treatment with 5% sodium hexametaphosphate (Fracas Lake samples) or 5% sodium pyrophosphate (Bear Lake samples) for at least three days. Charcoal fragments of 125 to 250 μm in size were counted using a dissecting microscope at magnification of ×25. The accumulation rates were calculated and used for fire reconstruction.

Organic content was determined by loss-on-ignition (Dean, 1974). The sediment samples were dried in an oven at 90–100ºC for at least one hour. After cooling to room temperature, dry weights were measured. Then, the samples were heated in a muffle furnace at 550ºC for at least one hour, and the weight losses were measured. The percentages of the weight losses to the dry weights were used as measurements of organic contents.

5. Chronology

Five accelerator mass spectrometry (AMS) radiocarbon dates were obtained from each of the Fracas Lake and the Bear Lake cores. Dates were obtained at sediment transitions and where significant changes were observed in pollen or macrofossils. All dates were obtained on terrestrial plant materials (Table 2). The corresponding calendar-year ages (cal yr B.P.) were obtained using the CALIB 3.0 computer program (Stuiver and Reimer, 1993). One of the dates (NSRL-10095) from the Fracas Lake core was rejected because of the apparently extraordinarily young age compared to other dates from this core. Throughout this paper, calendar dates are used for age description unless otherwise indicated. The bottom ages for cores from both lakes were nearly the same; both cores cover the past 13,500 calendar years (11,500 ^{14}C yr) (Fig. 3; Table 2). The age–depth models assume that the ages of the sediment surfaces at both sites are modern (Fig. 3).

6. Results

6.1. Fracas Lake

6.1.1. Sedimentation and aquatic vegetation

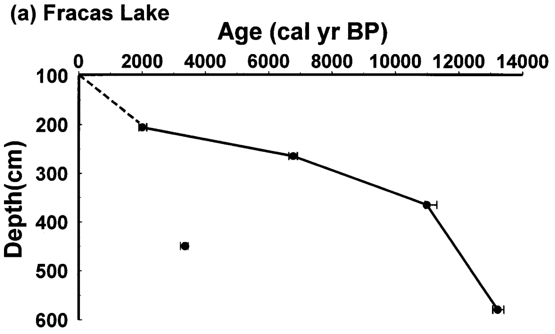
The sediments in the Fracas Lake core are generally composed of clay and fine sand with fine gravel (3–4 mm diameter) below 3.96 m depth, and gyttja above (Fig. 4). The average accumulation rate for the lower portion (below 3.65 m; >11,000 cal yr B.P.) was ~0.96 mm/yr (Table 3). Sediments are composed of clay, peaty gyttja, and fine sand with interbedded gravel. There are not enough dates to determine deposition rates for each layer. Between 5.09 and 5.85 m (fine sand with fine gravel interval), the pollen and macrofossil assemblages from

Table 2
AMS ^{14}C dates for the Fracas Lake and Bear Lake cores

Depth (cm)	Laboratory No.	Materials	Age (yr B.P.)	Calendar years
Fracas Lake				
206–207	NSRL-3517	charcoal	2070 ± 50	1999 (1889–2142)
265–266	NSRL-3455	charcoal	5950 ± 70	6781 (6642–6915)
365–366	NSRL-3411	spruce and ponderosa pine needles	9840 ± 70	10995 (10947–11317)
450–451	NSRL-10095	spruce, ponderosa pine needles and charcoal	3150 ± 50	3363 (3218–3465)
580–581	NSRL-3456	spruce needles, seed coats and wood	11320 ± 60	13228 (13072–13423)
Bear Lake				
312–313	NSRL-3022	ponderosa pine needles	3830 ± 60	4230 (3994–4412)
605–606	Beta-88937	ponderosa pine fascicle and attached needles	6590 ± 60	7425, 7403, 7399 (7335–7538)
680–681	NSRL-3410	ponderosa pine needles	8770 ± 70	9841, 9745, 9731, 9714, 9684 (9526–9928)
804–805	Beta-88938	spruce cone scales	10990 ± 60	12907 (13057–12754)
1000–1001	NSRL-3023	terrestrial plant pieces	11560 ± 60	13482 (13298–13726)

The corresponding calendar-year ages are listed in the last column. Means and 2σ ranges (in parentheses) are shown. For some ages, more than one mean is shown.

(a) Fracas Lake



(b) Bear Lake

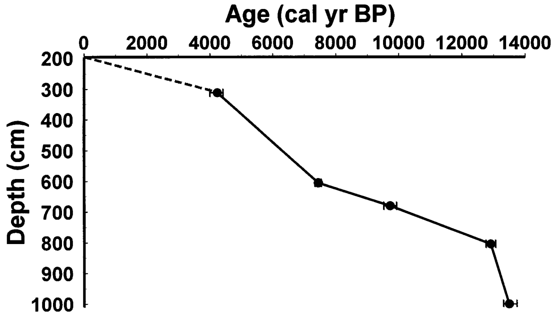


Fig. 3. Age–depth curves for (a) Fracas Lake, and (b) Bear Lake. Depths are counted from the water surfaces. The ages on the tops of the cores are assumed to be 0 cal yr B.P., and are linked with dotted lines. The error bars stand for the standard deviations of the dates.

different samples are very similar, but differ from samples above and below this interval. Some macrofossil types (lenticular *Carex* achenes, *Polygonum* seeds) were restricted to this interval. Organic content was lowest in this layer (<10%) (Fig. 4). Based on this evidence, we think this interval represents rapid deposition brought in by surface water. If so, the average accumulation rate for the other layers during this time period was ~0.64 mm/yr. After 11,000 cal yr B.P. (3.65–2.65 m), the accumulation decreased to ~0.24 mm/yr. Between 6800 and 2000 cal yr B.P. (2.65–2.06 m), the rate was lowest (0.12 mm/yr). After 2000 cal yr B.P. (above 2.06 m), the accumulation rate increased to 0.53 mm/yr (Table 3). These accumulation rates are generally typical compared with rates in northeastern North America, but the rate between 6800 and 2000 cal yr B.P. (0.12 mm/yr) was near the threshold rate (0.1 mm/yr) considered to indicate a possible hiatus (Webb and Webb, 1988).

Lenticular *Carex* achenes were abundant near the bottom of the core. They could be from aquatic or terrestrial species, but because they were most abundant in the sand layer likely formed through rapid deposition, they were probably from terrestrial *Carex* washed in with the sand. Macrofossils of other aquatic plants were not abundant during the Late Glacial, with only a few trigonous *Carex*/*Scirpus* achenes and

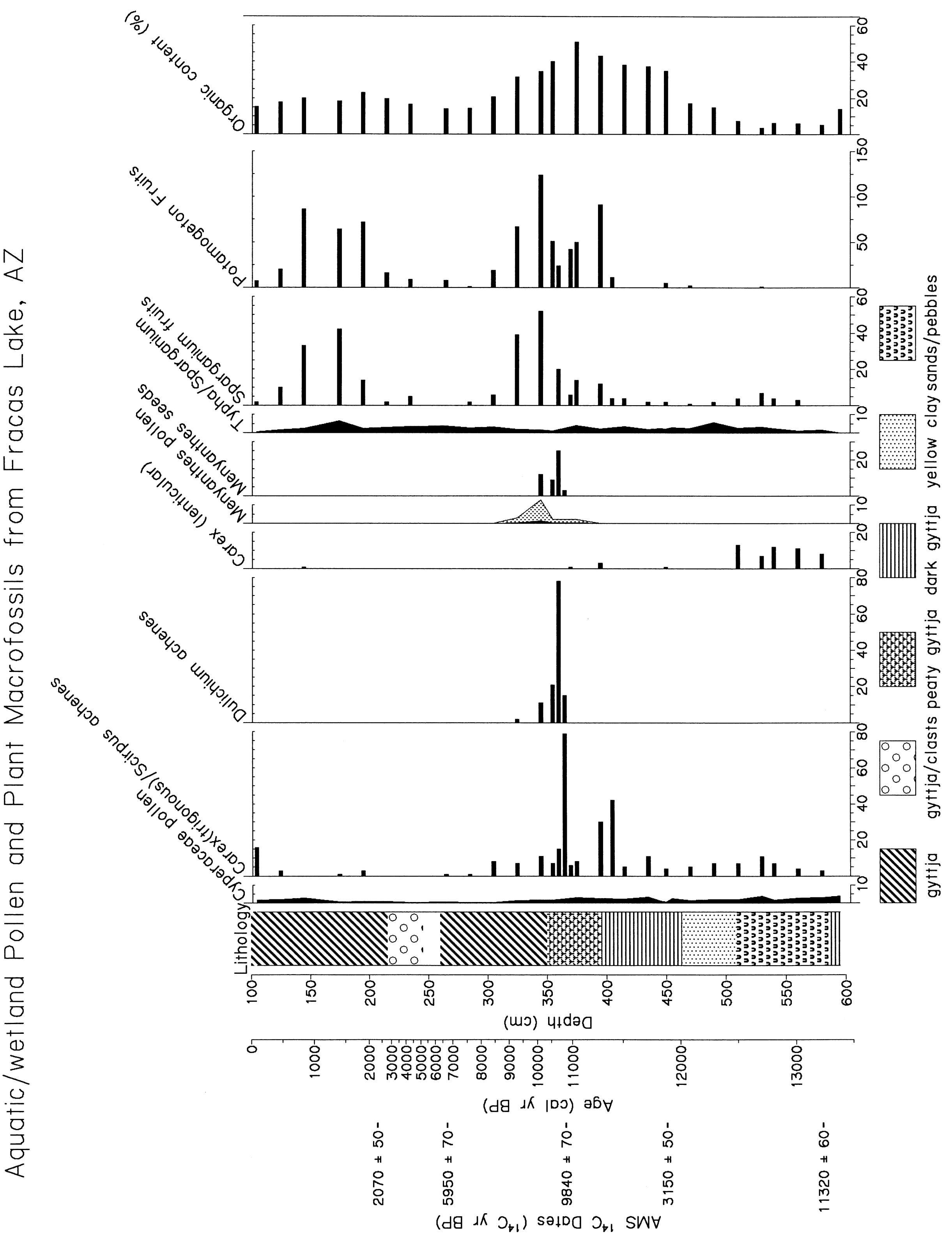

Aquatic/wetland Pollen and Plant Macrofossils from Fracas Lake, AZ
Organic content (%)
Potamogeton Fruits
Typha/Sparganium fruits
Menyanthes seeds
Menyanthes pollen
Carex (lenticular)
Dulichium achenes
Carex(trigonous)/Scirpus achenes
Cyperaceae pollen
Lithology
0 20 40 60
0 50 100 150
0 20 40 60
0 10
0 20
0 10
0 20
0 20 40 60 80
0 20 40 60 80
0 10
Depth (cm)
100 150 200 250 300 350 400 450 500 550 600
Age (cal yr BP)
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000
AMS 14C Dates (14C yr BP)
2070 ± 50
5950 ± 70
9840 ± 70
3150 ± 50
11320 ± 60
gyttja
gyttja/clasts
peaty gyttja
dark gyttja
yellow clay
sands/pebbles

Table 3
Sediments and accumulation rates from the Fracas Lake core and Bear Lake core

Depth) (m)	Sediments	Average accumulation rates (mm/yr)
Fracas Lake		
1.00–2.15	brown gyttja	0.53
2.15–2.45	brown gyttja with rocks (4–5 cm)	0.12
2.45–2.60	(missing)	
2.60–3.50	brown organic gyttja	0.24
3.50–3.96	black peaty gyttja	0.96
3.96–4.63	black clay	
4.63–5.09	yellow clay	
5.09–5.85	fine sands/rocks (2–3 mm)	
5.85–5.95	brown clay	
Bear Lake		
1.97–3.15	black gyttja	0.27
3.15–6.00	black peat	0.91
6.00–8.05	black gyttja	0.36
8.05–10.01	yellow-brown clay	3.41

Sparganium fruits represented. Aquatic-plant macrofossils were abundant from ∼11,500 to ∼8500 cal yr B.P. (∼4.15–3.05 m). Trigonous *Carex*/*Scirpus* achenes (probably mostly *Carex rostrata*), and *Sparganium* and *Potamogeton* fruits reached their highest abundance during this period. The organic content was also highest (∼35–57%). Abundant *Dulichium arundinaceum* (three-way sedge) and *Menyanthes trifoliata* (bogbean) seeds occurred from ∼10,995 to 10,000 cal yr B.P. (3.65–3.45 m depth).

Gravel-sized clasts (4–5 cm in diameter) were found between 2.45 to 2.15 m (∼6780–2700 cal yr B.P.). The deposition rate was very low (0.12 mm/yr), and organic content dropped to below 15%. Pollen and plant macrofossils were poorly preserved during this period. Aquatic plants were abundant again during the late Holocene (after ∼2700 cal yr B.P.). *Sparganium* and *Potamogeton* fruits reached another peak of abundance. *Typha*/*Sparganium* pollen also increased. Organic content increased to about 20%.

6.1.2. Upland plant pollen and plant macrofossils

> ca. 12,300 cal yr B.P. (below 5.00 m). The dominant pollen types were *Pinus* (∼40%), *Picea* (∼10%) and non-arboreal types (*Artemisia* ∼15%, Poaceae 13–16%, Tubuliflorae ∼5%, Cyperaceae 2–5%) (Fig. 5). *Picea* needles and seeds were abundant. Five spruce needles were identified to species based on anatomical structures. Four were *Picea engelmannii* (three at 5.60 m depth, ∼13,020 cal yr B.P.; one at 5.10 m, ∼12,500 cal yr B.P.), and one was *Picea pungens* (5.60 m) (Fig. 5; Table 4). The only *Abies* needle fragment occurred at 5.10 m depth, and was identified as *A. lasiocarpa* (Fig. 5; Table 5). *Pinus flexilis* pollen occurred consistently at low percentages (2–4%). *Pinus edulis* was also a persistent trace component (∼1%).

The bottom sample was quite different from the others, having much lower percentages of *Picea* and Poaceae pollen (1 and 6%, respectively), much higher percentages of *Artemisia* (32%), and no macrofossils. Clustering analysis suggests it should be placed in a separate pollen zone.

12,300–11,000 yr B.P. (5.00 – 3.65 m). *Picea* and *Artemisia* pollen percentages increased to ∼15 and >20%, respectively. The maxima for these types persisted until ∼11,000 yr B.P. Lack of well-preserved *Picea* needles prevented us from identifying species in most sediments of this zone. Six *Picea pungens* needles were identified near the top of the zone (one at depth of 3.75 m, ∼11,100 cal yr B.P., five at 3.65 m, ∼10,995 cal yr B.P.; Fig. 5; Table 4). *Pinus edulis* pollen persisted (1–2%). Tubuliforae and Poaceae decreased gradually. *Pinus* pollen increased rapidly from 40 to more than 60%, ∼12,000 cal yr B.P., while *Picea* and *Artemisia* pollen dropped rapidly to <5 and 10%, respectively. This episode lasted only a short time (<500 years). Then *Pinus* decreased to ∼40% again rapidly. *Picea* and *Artemisia* increased to respective maxima of 15% and 25–30%, which persisted until the end of this zone (Fig. 5).

11,000–8400 yr B.P. (3.65–3.05 m). *Pinus* pollen percentages increased after 11,000 yr B.P. to become

Fig. 4. Aquatic/wetland pollen and plant macrofossil diagram for Fracas Lake. AMS radiocarbon dates, corresponding calendar-year ages, and lithology are on the left of the diagram. Shaded silhouettes represent pollen percentages. Ten-fold exaggeration (stippled) highlights the percentages of infrequent pollen types. Histograms represent macrofossil concentrations (numbers per 70 cm^3 of sediment) or organic contents.

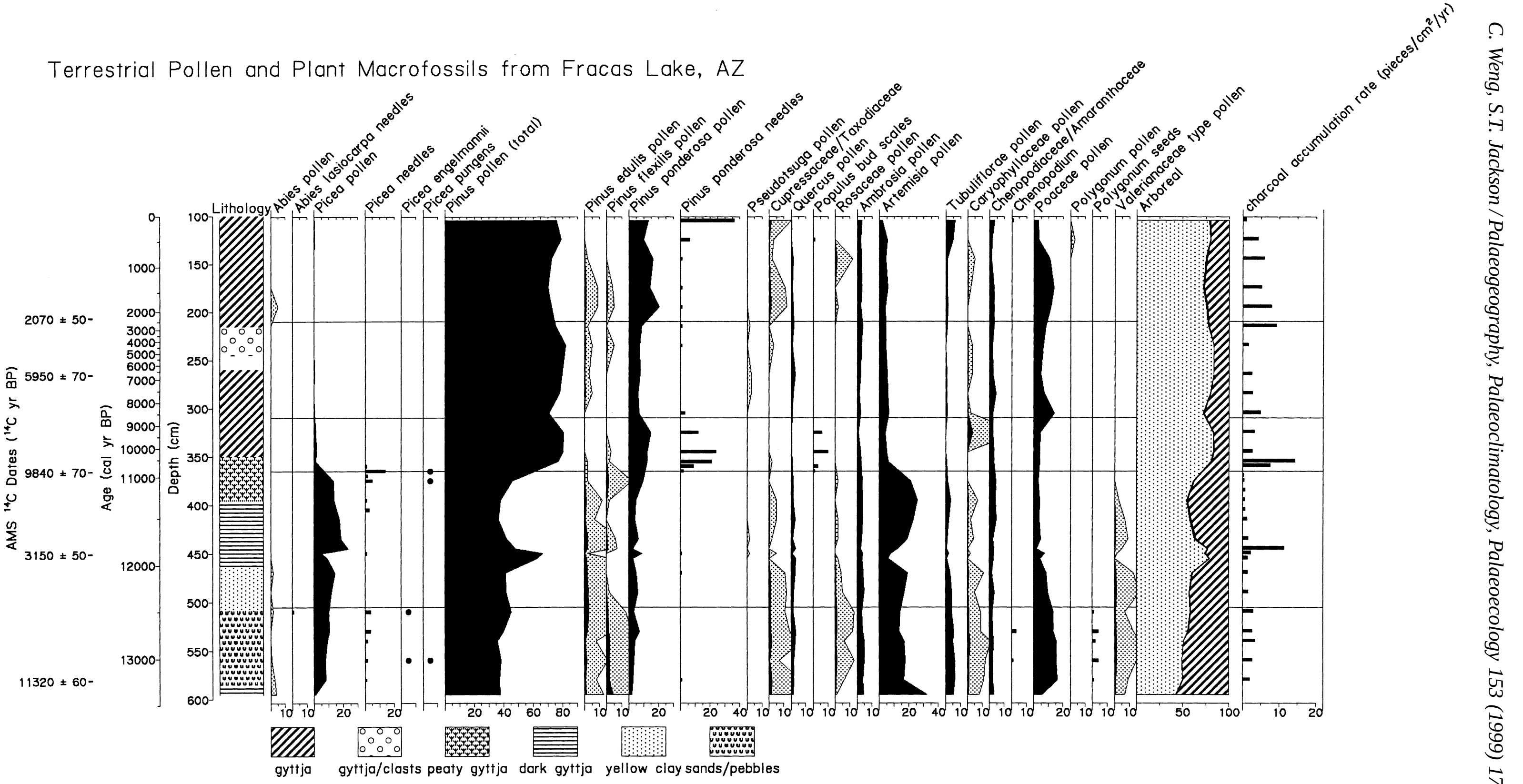


Fig. 5. Terrestrial pollen and plant macrofossil diagram for Fracas Lake. AMS radiocarbon dates, corresponding calendar-year ages, and lithology are on the left of the diagram. Shaded silhouettes represent pollen percentages. Dots in some plots indicate presence of needles. Histograms represent macrofossil concentrations (numbers per 70 cm^3 of sediment) or charcoal accumulation rate. Different zones are separated by horizontal lines.

Table 4
Species-level identification of *Picea* needles and needle pieces from Fracas Lake and Bear Lake. Depths and ages of samples are also shown

Age (cal yr B.P.)	Depth (m)	*P. engelmannii*	*P. pungens*	Indetermined
Fracas Lake				
10995	3.65		5	
11099	3.75		1	1
12501	5.10	1		1
12709	5.30			2
13020	5.60	3	1	
Bear Lake				
920	2.22			1
2391	2.62			3
3127	2.82	2	2	7
3494	2.92		2	4
4230	3.12	1		7
4663	3.52		1?	7
4977	3.81		2	5
6167	4.91		2	5
6599	5.31		1	1
7184	5.85			3
9725	6.80		1	4
10301	7.00	2		3
10802	7.20	1		5
11303	7.40			3
11679	7.55	2		4
12682	7.95	1		
12910	8.05	2		4

Table 5
Species-level identification of *Abies* needles and needle pieces from Fracas Lake and Bear Lake. Depths and ages of samples are also shown

Ages (cal yr B.P.)	Depth (m)	*Abies lasiocarpa*	*Abies concolor*
Fracas Lake			
12501	5.10	1	
Bear Lake			
184	2.02	2	
1655	2.42	6	
3126	2.82	2	
4230	3.12	5	
4669	3.52	5	
5207	4.01	1	1
5426	4.21	2	
5645	4.41	1	
6194	4.91	2	
6414	5.11	1	
6853	5.51	1	
7225	5.85	2	
7335	5.95	1	
7445	6.05	1	
9117	6.60	1	
11679	7.55	26	
12180	7.75	17	

the dominant type (~80%). Most identifiable *Pinus* pollen was *Pinus ponderosa*. *Pinus ponderosa* needles and *Populus* bud scales were very abundant in this zone. *Picea* pollen dropped rapidly from more than 13% to less than ~1.5%, and *Picea* macrofossils disappeared from the record. *Artemisia* and Tubuliflorae pollen declined to ~6%. This zone matches the early Holocene period of deep water and aquatic-plant dominance, although we did not use aquatic plants in the zonation.

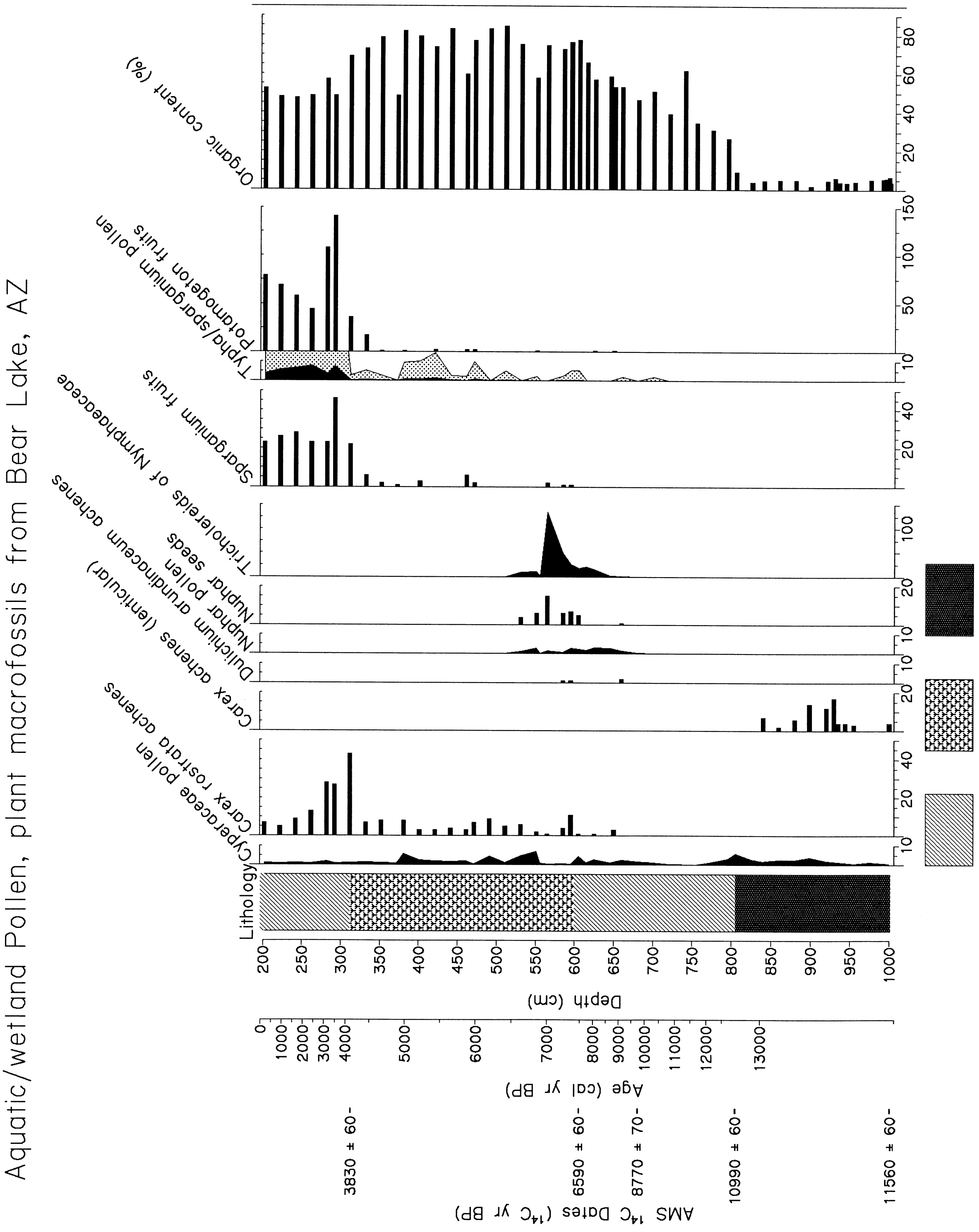
Ca. 8400–2000 yr B.P. (3.05–2.06 m). *Pinus* pollen (primarily *P. ponderosa*) was still dominant. However, *Pinus* pollen grains identifiable to species were fewer due to poor preservation. Percentages of Poaceae increased at the base of this zone. Macrofossils were rare in the entire zone, probably due to poor preservation.

Ca. 2000 — 0 yr B.P. (above 2.06 m). *Pinus* pollen decreased slightly to ~70% at the beginning of the zone, then increased to >75% at the end of the zone. Identified *Pinus ponderosa* pollen increased. Poaceae pollen increased to >10%.

6.1.3. Charcoal and fire records

Charcoal accumulation rates were low (~3.0 pieces cm^{-2} yr^{-1} before ca. 12,300 cal yr B.P. (in the bottom zone). The accumulation rates were even lower between 12,300 and ~10,500 cal yr B.P. (3.50 m) (only ~1.5 pieces cm^{-2} yr^{-1}). The only exception was at a depth of 4.45 m (~11,800 cal yr B.P.), where the charcoal accumulation rate was very high (11.4 pieces cm^{-2} yr^{-1}). After this peak, charcoal accumulation rates dropped to even lower levels (<1.0 pieces cm^{-2} yr^{-1}) than before.

The depth of 3.50 m (10,500 cal yr B.P.) is a critical level for fire history. At this level, charcoal accumulation rates increased rapidly to 14.3 pieces cm^{-2} yr^{-1}, and continued to be moderately high (~2.5–5.0 pieces cm^{-2} yr^{-1}) above it, then decreased at ~2.50 m (5000–3000 cal yr B.P.), the interval in which clasts were deposited. After ~2100 cal yr B.P. (2.10 m), charcoal accumulation rate in-


Aquatic/wetland Pollen, plant macrofossils from Bear Lake, AZ
Organic content (%)
Potamogeton fruits
Typha/Sparganium pollen
Sparganium fruits
Trichosclereids of Nymphaeaceae
Nuphar seeds
Nuphar pollen
Dulichium arundinaceum achenes
Carex achenes (lenticular)
Carex rostrata achenes
Cyperaceae pollen
Lithology
gyttja
peat
clay
Depth (cm)
200
250
300
350
400
450
500
550
600
650
700
750
800
850
900
950
1000
Age (cal yr BP)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
11000
12000
13000
AMS ¹⁴C Dates (¹⁴C yr BP)
3830 ± 60
6590 ± 60
8770 ± 70
10990 ± 60
11560 ± 60
20
40
60
80
50
100
150
10
20
40
100
20
10
10
20
20
40
10

creased to 9.2 pieces cm^{-2} yr^{-1}, and then decreased gradually to the top of the sequence.

6.2. Bear Lake

6.2.1. Sedimentation and aquatic vegetation

Sediments of Bear Lake are composed of inorganic clay below 8.00 m, with gyttja and peat above (Fig. 6). AMS dates from the bottom of the clay layer and the bottom of the gyttja layer just above the clay were 13,482 cal yr B.P. (11,560 ^{14}C yr B.P.) and 12,907 cal yr B.P. (10,990 ^{14}C yr B.P.), respectively. The age difference was only 575 years over a depth of almost two meters, and the average deposition rate was accordingly high (3.4 mm/yr). Thin sand bands (2–3 mm thick) were interbedded in the clay layer. Organic content of the clay was <15%. Similar to Fracas Lake, lenticular *Carex* achenes were abundant in Bear Lake. Since the slopes adjacent to Bear Lake are steep, the lenticular *Carex* achenes may have been washed into the lake with the sediments from the surrounding uplands. Gyttja deposition occurred in the basin from 12,900 to 7400 cal yr B.P. (8.04 to 6.05 m depth), followed by peat deposition. Abundance of *Nuphar* pollen, seeds and Nymphaeaceae tricholereids (probably from *Nuphar* leaves) indicates that *Nuphar* was abundant in the pond at the time of this mid-Holocene sediment change (Fig. 6). *Carex rostrata* also occurred in the pond. *Sparganium* and *Potamogeton* fruits were very rare. *Dulichium arundinaceum*, extinct locally today, also occurred between 9200 and 7200 cal yr B.P.

Between ~6000 and 4200 yr B.P., *Nuphar* and *Dulichium arundinaceum* disappeared from Bear Lake, while *Carex rostrata* and *Sparganium* increased in abundance. At ~4200 cal yr B.P., the sediment changed from peat to gyttja as the lake deepened, and aquatic plants became more abundant. *Typha/Sparganium* pollen was high; *Carex rostrata* achenes, and *Sparganium* and *Potamogeton* fruits were very abundant.

6.2.2. Upland plant pollen and plant macrofossils

Twenty-three terrestrial pollen and plant macrofossil taxa were used for zonation (Table 1), resulting in four pollen and plant macrofossil zones for the Bear Lake core (Fig. 7).

>12,900 cal yr B.P. (below 8.05 m). Dominant pollen types were *Artemisia*, Poaceae, Tubuliflorae and Cupressaceae/Taxodiaceae. Arboreal pollen percentages were very low; *Abies* and *Picea* pollen percentages were <5%. *Abies* macrofossils were absent, and *Picea* needles were scarce. *Pinus* pollen percentages were <35%. Identifiable *Pinus ponderosa* pollen was low, but some *Pinus flexilis* and *Pinus edulis* grains were identified. *Polygonum* pollen and *Selaginella* microspores were also important in the pollen assemblages.

Ca. 12,900–ca. 10,300 cal yr B.P. (8.05–7.00 m). The bottom of this zone was characterized by rapid increases in percentages of *Picea and Abies* pollen (Fig. 7). *Picea* increased from <5 to >10%, exceeding 30% at some levels. Abundant *Picea* needles were found (from 20 to >100 per 70 cm^3 sediment). All identified needles were from *Picea engelmannii* (Fig. 7; Table 4). The *Abies* pollen increase followed the *Picea* pollen increase at 12,500 cal yr B.P. *Abies lasiocarpa* needles were also abundant in this period (Fig. 7; Table 5). *Pinus* pollen initially increased to about 40%, and increased further ~11,500 cal yr B.P., to 69%, while *Picea*, *Artemisia*, *Ambrosia* and *Poaceae* pollen decreased. The *Pinus* peak was short, and was followed by a rapid drop to ~40% again. *Pinus flexilis* pollen was rare in this zone, and *Pinus edulis* was also low. *Artemisia* and *Ambrosia* pollen remained moderately high (~10 and 3%, respectively), with subsequent increases in *Ambrosia* and Chenopodiaceae/Amaranthaceae pollen in late in this period. Poaceae, Cyperaceae, and Tubuliflorae dropped to very low percentages. *Populus* bud scales (probably *Populus tremuloides)* first appeared in the upper half of this zone.

Ca. 10,300 to ca. 4400 cal yr B.P. (7.00–3.32 m). *Pinus* pollen was the dominant pollen type (60 to

Fig. 6. Aquatic/wetland pollen and plant macrofossil diagram for Bear Lake. AMS radiocarbon dates, corresponding calendar-year ages, and lithology are on the left of the diagram. Shaded silhouettes plots represent pollen percentages and tricholereids of Nymphaeaceae. Ten-fold exaggeration (stippled) highlights the percentages of infrequent pollen types. Histograms represent macrofossil concentrations (numbers per 70 cm^3 of sediment) or organic contents.

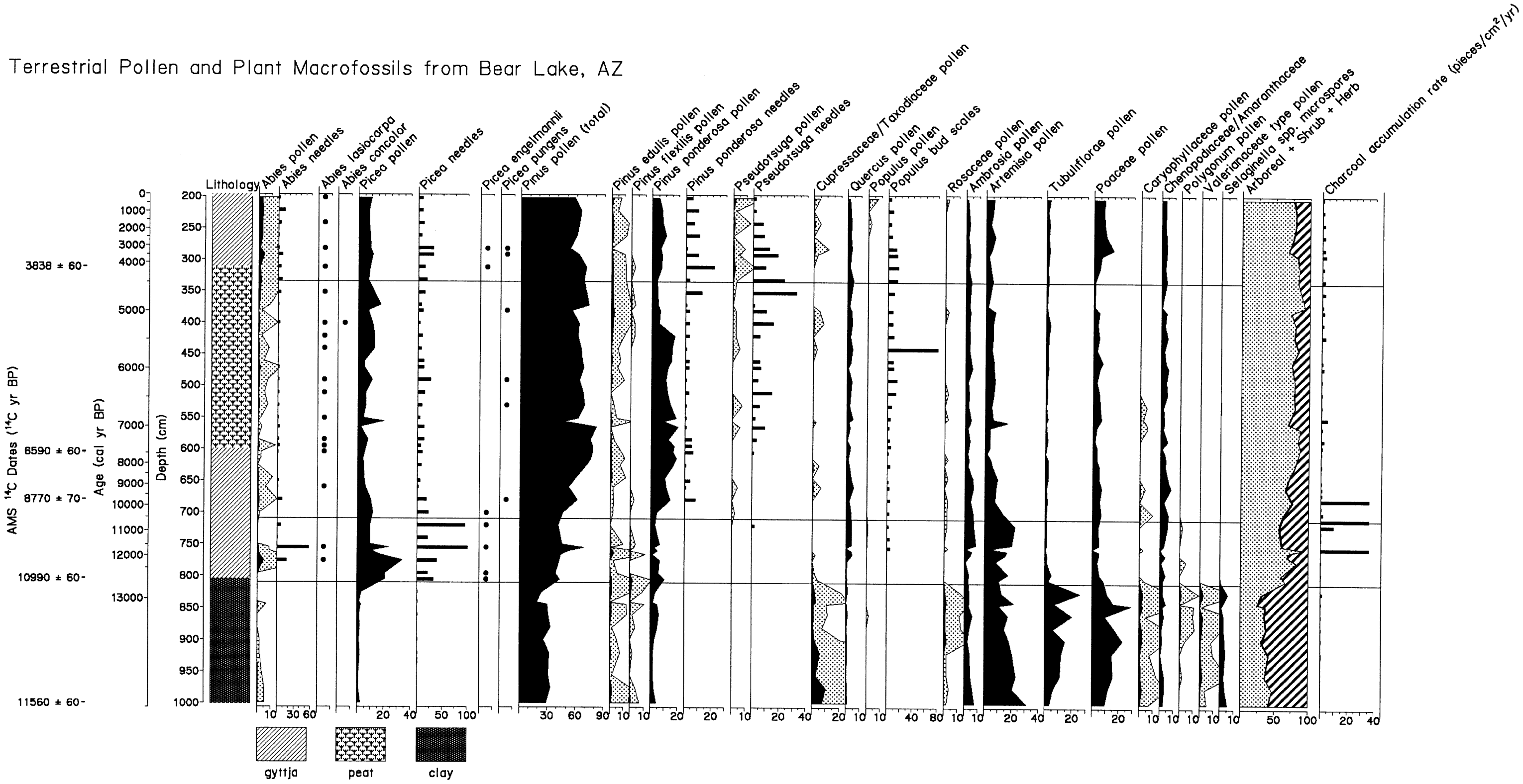


Fig. 7. Terrestrial pollen and plant macrofossil diagram for Bear Lake. AMS radiocarbon dates, corresponding calendar-year ages, and lithology are on the left of the diagram. Shaded silhouettes represent pollen percentages. Dots in some plots indicate presence of needles. Histograms represent macrofossil concentrations (numbers per 70 cm^3 of sediment) or charcoal accumulation rate. Different zones are separated by horizontal lines.

$>$80%). Nearly all of the identifiable *Pinus* pollen was *Pinus ponderosa*. *Pinus ponderosa* macrofossils (needles) appeared for the first time at ca. 9730 cal yr B.P. and were consistently present thereafter. *Pseudotsuga* pollen and needles became increasingly abundant after ca. 7500 cal yr B.P. *Picea* and *Abies* pollen and macrofossils decreased through this period relative to the previous period. Almost all identified spruce needles were from *Picea pungens* (except two needles from the bottom sample; Fig. 7; Table 4). Most *Picea* needles were not identified because of poor preservation of resin ducts.

Ca. 4400 to 0 cal yr B.P. (3.32–0 m). *Abies* pollen and macrofossils increased in abundance again. *Picea* needles reached another peak at the beginning of this zone, and then decreased slightly. Both *Picea engelmannii* and *Picea pungens* needles were found in this zone after $\sim$4230 cal yr B.P. (3.12 m depth). *Pinus* pollen percentages remained high, and needles of *Pinus ponderosa* were more numerous than before. *Pseudotsuga* pollen and needles were also frequent.

6.2.3. Charcoal and fire records

Charcoal fragments were absent or scarce before the increase of *Picea* and *Abies* pollen and macrofossils at 12,900 cal yr B.P. (below 8.05 m). Charcoal accumulation rates were very low prior to 12,000 cal yr B.P. ($<$1.0 pieces cm^{-2} yr^{-1}). After *Picea* and *Abies* pollen reached their peaks ($\sim$7.75 m, $\sim$12,000 cal yr B.P.), charcoal accumulation rate increased rapidly to over 35 pieces cm^{-2} yr^{-1} at $\sim$7.55 m ($\sim$11,600 cal yr B.P.). Many charred *Picea* and *Abies* needles were found in the macrofossil assemblages. Meanwhile, both *Picea* and *Abies* pollen percentages began to decline. At least two other high charcoal peaks followed ($\sim$10,300 and $\sim$9,800 cal yr B.P.). After $\sim$9800 cal yr B.P., charcoal accumulation rates dropped again ($<$1.0 pieces cm^{-2} yr^{-1}). After $\sim$4700 cal yr B.P. ($\sim$3.50 m), however, charcoal concentration increased slightly to over 2.0 pieces. After 3000 cal yr B.P., it dropped gradually to 1.0 pieces cm^{-2} yr^{-1} on the top of the core.

7. Discussion

7.1. Basin hydrology and aquatic vegetation history

During the Late Glacial, both Fracas Lake and Bear Lake were apparently unproductive and supported few aquatic plants. High deposition rates, high mineral content, and low organic content in the sediments indicate the shorelines and surrounding uplands were sparsely vegetated and subject to erosion.

Aquatic plants became established in Fracas Lake after 11,500 cal yr B.P. in response to increasing temperature. *Carex* (probably mainly *Carex rostrata*), *Sparganium*, and *Potamogeton* dominated during the latest Glacial and early Holocene (11,500–8500 yr B.P.). *Dulichium arundinaceum* and *Menyanthes trifoliata* also occurred between $\sim$10,995 and 10,000 yr B.P. Today, the nearest occurrences of *Dulichium arundinaceum* are in California (Mason, 1957) and the Yellowstone region of Wyoming (Rocky Mountain Herbarium). The nearest occurrences of *Menyanthes trifoliata* are in central eastern Arizona (Kearney and Peebles, 1960) and southern Utah (Welsh et al., 1993). These two species disappeared from Fracas Lake at $\sim$9100 and $\sim$10,000 cal yr B.P., respectively.

After $\sim$8500 cal yr B.P., aquatic plants became rare, organic content and deposition rate decreased, and preservation of pollen and plant macrofossils declined. Between $\sim$6800 and 2700 yr B.P., coarse clasts were deposited in the lake, and the very low accumulation rate (0.12 mm/yr) may indicate a hiatus or severe loss of temporal resolution (Webb and Webb, 1988). This evidence indicates a decline in lake-level due to dry climate. Decomposition of organic materials in a shallow basin can explain the low organic content, low accumulation rate and poorly preserved pollen and macrofossils. A severe drop in lake levels during the mid-Holocene in this region was reported in several lakes on the southern Colorado Plateau (e.g. Potato Lake, Anderson, 1993; Walker Lake, Hevly, 1985; Stoneman Lake, Hasbargen, 1994). The records from these lakes support our inference that the mid-Holocene was a very dry period in the region. In Fracas Lake, however, except for the clasts, sediment composition is similar to that at lower horizons (all are gyttja), which suggests that the hydroperiod in the basin was continuous, and that there is no depositional hiatus in the sediments. We do not know how the clasts were transported to the center of the pond. Because the shore was not steep, we do not believe they rolled in from the shore. They are not associated with layers of coarse clastic or organic debris, so transport in rivulets is unlikely. They may have been brought in on the hooves of ungulates, or by activities of native Americans.

After ~2000 cal yr B.P., *Sparganium* and *Potamogeton* were once again abundant in the lake. Increasing effective moisture (decreasing temperature and/or increasing precipitation) in the late Holocene led to increasing water levels.

Aquatic plants began to establish in Bear Lake at ~9100 cal yr B.P. (6.60 m depth). Cold water may have restricted establishment of aquatic plants in Bear Lake before 9100 cal yr B.P. Between 9100 and 6600 cal yr B.P., *Nuphar* was dominant. *Dulichium arundinaceum* also grew in the lake between ~9200 and 7200 yr B.P. The sediment change from gyttja to peat at ~7400 cal yr B.P. indicates a drop in water level. After ~6600 cal yr B.P., declining water level led to local extinction of *Nuphar*, which was previously abundant. The lake was shallowest between 6600 and 4230 cal yr B.P.

At ~4200 cal yr B.P., a sediment change from peat to gyttja indicates higher water levels owing to increased effective moisture. *Carex rostrata*, *Sparganium*, and *Potamogeton* became more abundant. The floating mat that now covers much of the surface probably formed at this time.

Hydrological changes at the two lakes may not have coincided precisely. Prior to ~9100 cal yr B.P., high water levels supported abundant aquatic plants in Fracas Lake, while Bear Lake was perhaps too cold or too deep for aquatic plants to establish. The dry period commenced at ~8500 cal yr B.P. in Fracas Lake, while water-level decline was not recorded at Bear Lake until ~7400 cal yr B.P. The driest period for Bear Lake was probably after ~6400 cal yr B.P., when *Nuphar* disappeared. The late Holocene lake level rise apparently occurred at ~4230 cal yr B.P. in Bear Lake, while the corresponding late Holocene rise occurred in Fracas Lake at ~2000 cal yr B.P. The timing differences in the two ponds resulted in part from different precipitation and evaporation rates at different elevations. Higher precipitation and lower evaporation rates delayed the mid-Holocene water-level decline at Bear Lake, while lower precipitation and higher evaporation rates at Fracas Lake delayed late Holocene water level rise relative to Bear Lake.

7.2. Vegetation history and environment

7.2.1. Fracas Lake area

Fracas Lake was surrounded by *Picea* forest from ca. 13,300 to 10,995 yr B.P. *Picea engelmannii* was probably the dominant species. *Abies* did not occur locally. The forest was open and perhaps parklike. *Artemisia*, *Ambrosia*, Poaceae, Cupressaceae (probably *Juniperus communis*) and Asteraceae plants probably grew in open areas or as understory. Though *Pinus* pollen percentages (mainly *Pinus ponderosa*) were high (up to 40%; Fig. 5), *Pinus* macrofossils were absent. According to a study of modern pollen assemblages in the region (Jackson and Smith, 1994), the *Pinus* pollen could have originated from populations at lower elevations, or from distant populations far to the south. *Pinus edulis* and *Pinus flexilis* probably grew at nearby lower elevations, because their pollen was relatively abundant, and was found in Bear Lake sediments at the same time (Fig. 7). Today, *Pinus flexilis* does not grow on the Kaibab Plateau or in adjacent southern Utah (Little, 1971; personal observations). However, macrofossils of this species were dominant in packrat middens before ~11,000 cal yr B.P. (10,000 ^{14}C yr B.P.) at many lower sites (from 1390 to 2200 m) in southeastern Utah, northwestern New Mexico and northeast Arizona (Betancourt, 1984, 1990). Cole (1990) also reported abundant *P. flexilis* needles in packrat middens older than 14,000 cal yr B.P. (12,000 ^{14}C yr B.P.) collected between 1500 and 2100 m elevation in the Grand Canyon.

Two hypotheses can be proposed to explain the occurrence of *P. flexilis* pollen in Fracas Lake and Bear Lake. First, *P. flexilis* grew on the Kaibab Plateau at elevations below 2500 m. An alternative hypothesis is that the *Pinus flexilis* pollen was transported long-distance from southeastern Utah, northeastern Arizona, northwestern New Mexico, or the Coconino Plateau (just across the Grand Canyon, where *Pinus flexilis* grows today) in northern Arizona. Cole's (1990) data support the first hypothesis.

However, we lack direct evidence from sites on the Kaibab Plateau below Fracas Lake to confirm it.

After ca. 12,300 cal yr B.P., *Picea* forest around Fracas Lake probably became less open. *Picea pungens* replaced *Picea engelmannii* as the dominant species. Poaceae, Tubuliforae, and Cupressaceae (probably *Juniperus*) populations decreased. However, *Artemisia* continued to remain abundant. At ~12,000 cal yr B.P., climate may have become warmer and wetter, and *Pinus ponderosa* apparently moved upward closer to Fracas Lake or became denser, producing a *Pinus* pollen peak. However, the high *Pinus* peak only lasted a short time, followed by a decrease during which *Picea* and *Artemisia* pollen increased to their highest percentages in the entire sequence. These two episodes correspond approximately to the time of the Allerod warm period and Younger Dryas cool period (Dansgaard et al., 1971; Ruddiman and McIntyre, 1981). The cool and dry Younger Dryas period may have suppressed growth of *Pinus ponderosa* and led to expansion of *Picea* and *Artemisia*.

At ca. 11,000 yr B.P., *Pinus ponderosa* became established near Fracas Lake. Meanwhile, *Picea pungens* decreased and disappeared rapidly. This decrease was apparently a result of competition with *Pinus ponderosa* mediated by climate warming. Since the *Picea* forest was probably open, it was easy for *Pinus ponderosa* trees to disperse and germinate seeds, and invade into the *Picea* forest when climatic conditions were favorable. *Populus* trees were relatively abundant at this time. The charcoal evidence does not indicate that fire played a role in the transition. After the transition, *Pinus ponderosa* was dominant through the remainder of the Holocene.

7.2.2. Bear Lake area

The Bear Lake area, 260 m higher than Fracas Lake, experienced a somewhat different history. According to the pollen and macrofossil records, the highest portion of the Kaibab Plateau was treeless before ca. 12,900 yr B.P. The *Polygonum*, Valerianaceae-type pollen and *Selaginella* spores may be from alpine species. Low arboreal pollen percentages also suggest that Bear Lake was surrounded by alpine tundra, which does not exist on the Kaibab Plateau today. The other dominant plants of the tundra were probably *Artemisia*, Cupressaceae (probably *Juniperus communis*) and other Asteraceae plants. Abundant *Juniperus* cf. *osteosperma* foliage was found in packrat middens of this period at lower elevations in the Grand Canyon (Cole, 1990), which indicates that some Cupressaceae pollen could be from *Juniperus* populations at lower elevations. The lenticular-seeded *Carex* was probably also an important element of the alpine vegetation. Tree line was below the altitude of Bear Lake, but not much lower because a few fragments of *Picea* needles were found in sediments dating before 11,000 cal yr B.P., and *Picea* pollen was persistent at about 2–3% in these samples. Macrofossils are usually transported over only short distances (Dunwiddie, 1987), and *Picea* pollen is neither productive nor effective at long-distance dispersal (Jackson, 1990; Jackson and Smith, 1994). The persistence of *Picea* needles and relatively high percentages of *Picea* pollen indicate that *Picea* trees were in the vicinity of Bear Lake. Based on this evidence, we infer that alpine tundra was restricted to the highest parts of the plateau, and that scattered *Picea* trees or shrubs occurred. Bear Lake is located near the highest elevation of the plateau.

At about 12,900 cal yr B.P., *Picea engelmannii* and *Abies lasiocarpa* moved upward to occupy the area near Bear Lake. Between 12,900 and 10,800 cal yr B.P., *Picea* and *Abies* were most abundant. *Artemisia* may have been in open areas of the forest, or possibly some *Artemisia* pollen was transported from lower elevations.

Similar to Fracas Lake, a *Pinus* pollen peak was found ~11,500 cal yr B.P., followed by a decrease of *Pinus* and increase of *Artemisia*, *Ambrosia* and *Picea*. This may reflect the Younger Dryas cooling after the Allerod warming period. However, the *Pinus* peak represents only one sample, and we do not have strong evidence indicating the time equivalence of these events.

After ca. 10,800 cal yr B.P., the abundance of *Picea* and *Abies* near Bear Lake decreased, and *Pinus ponderosa* trees moved upward and invaded the Bear Lake area at ~9725 cal yr B.P. At this time, *Picea pungens* invaded, replacing *P. engelmannii* as the major spruce species. We cannot exclude the appearance of *Picea engelmannii* because many needles were not identified due to lack of resin ducts.

According to our study of *Picea* needles, those without resin ducts most likely belong to *P. engelmannii* (Weng, 1998). However, we have no direct evidence that *P. engelmannii* persisted at the site. The invasion of *P. pungens* at least partially (if not totally) replaced *P. engelmannii*. *Pinus ponderosa*, *Picea pungens* and *Abies lasiocarpa* trees co-dominated closed forests near Bear Lake from 9725 to 8000 yr B.P. *Populus* trees were probably a co-existing component. After ~8,000 yr B.P., *Pseudotsuga* arrived and became codominant with the other species.

Picea engelmannii rejoined the mixed conifer forest near Bear Lake ~4,000 yr B.P. However, *Picea pungens* persisted at the site during the late Holocene. The modern vegetation was formed at this time following cooler and moister climate.

7.3. Early Holocene environment and migration of Pinus ponderosa

A few *Pinus ponderosa* needle fragments were found in sediments of Fracas Lake prior to 11,000 cal yr B.P. (9840 ^{14}C yr B.P.), in association with high *Pinus* pollen percentages (~40%). We suspect that *Pinus ponderosa* populations existed at lower elevations on or below the Kaibab Plateau. However, we do not have direct evidence to support this hypothesis. In the Grand Canyon, relatively few *Pinus ponderosa* macrofossils were found from packrat middens at elevations between 1770 and 1990 m with ages between ~9500 and 10,000 cal yr B.P. (8590–9070 ^{14}C yr B.P.) (Cole, 1990). No packrat middens dating between 14,200 and 10,000 cal yr B.P. (12,170 and 9070 ^{14}C yr B.P.) were found at elevations above 1450 m (Cole, 1990). Middens dated at ~14,900 and 14,200 cal yr B.P. (12,660 and 12,170 ^{14}C yr B.P.) from 2050 m elevation contained *Picea engelmannii/pungens*, *Abies concolor* and *Pinus flexilis*, which grow at elevations higher than *Pinus ponderosa* today. Late glacial *Pinus ponderosa* population may have been distributed at elevations between 1450 and 2050 m, with upward movement occurring between 14,000 and 11,000 cal yr B.P., mediated by postglacial warming.

Pinus ponderosa reached Fracas Lake at ~10,995 cal yr B.P. (9840 ^{14}C yr B.P., range 11,008–10,976 cal yr B.P.), and Bear Lake at ~9725 cal yr B.P. (8770 ^{14}C yr B.P., range 9884–9645 cal yr B.P.). Assuming the temperature change during this period was gradual and unidirectional (warming), and the movement of *Pinus ponderosa* was also unidirectional (upward) and in equilibrium with climate, we can infer the 'climbing' rate of the species between 11,000 and 9700 cal yr B.P. was 19 to 24 m elevation/century (mean 20.5 m/century). Using the average annual lapse rate of 0.65ºC/100 m (Lydolph, 1985), we infer that the average increase in annual temperature was 1.25 to 1.56ºC in 1000 years (mean ~1.3ºC).

Pinus ponderosa grows above the elevation of Bear Lake today. Thus, between 10,995 yr B.P. and 9725 cal yr B.P., when *P. ponderosa* reached Bear Lake, the Kaibab Plateau was colder and wetter (according to aquatic plants and lake levels) than today. This inference is similar to that of Betancourt (1990) for the Colorado Plateau region of southeast Utah. Between ~11,100 and ~6800 cal yr B.P. (10,000 and 6000 ^{14}C yr B.P.), montane and transitional forest elements were at lower elevations than today, from which Betancourt (1990) inferred that the Colorado Plateau was wetter. In the eastern Great Basin, the range of current pinyon–juniper woodlands was dominated by montane plants (*Pinus flexilis, Juniperus scopulorum, Populus tremuloides* and *Amelanchier utahensis*) during the early Holocene, from which Thompson (1990) also inferred cooler-than-modern climatic conditions. In the Sonoran Desert, the persistence of woodland plants at low elevations also suggests that summer temperatures were cooler than today (Van Devender, 1990).

7.4. Fire history and its role in vegetation dynamics

According to charcoal records, fires were uncommon in the Fracas Lake area before about 10,600 cal yr B.P., about 300 years after the first arrival of *Pinus ponderosa*. At ~11,800 cal yr B.P., one local fire probably occurred in *Picea* woodland. After the establishment of *Pinus ponderosa* at 11,000 cal yr B.P., fire occurrence increased greatly. Fire plays an important role in maintaining *Pinus ponderosa* forest today (Habeck and Mutch, 1973; Kercher and Axelrod, 1984; Covington and Sackett, 1986; Oliver and Ryker, 1990; Habeck, 1994). Fire frequency is very high (1–16 years) in *Pinus ponderosa* forests of the southwestern United States (Swetnam and Dieterich, 1985; Baisan and Swetnam, 1990; Swetnam and Baisan, 1996). The increase of fire incidence after 10,600 cal yr B.P. probably resulted from establishment of *Pinus ponderosa*. Climatic warming and perhaps greater seasonal drought contributed to the increase in fires.

In the Bear Lake area, few or no local fires occurred before ~12,000 cal yr B.P. We suggest that before the arrival of *Picea* and *Abies* trees, fuels were insufficient to support large fires. During this period, climate was also cool and relatively wet, which would also have suppressed occurrence of fires.

At Bear Lake, the initial decline of *Picea* and establishment of *Pinus ponderosa* were separated by a gap of about 400 years (Fig. 7). Apparently, the fall of *Picea* was not a result of invasion of *Pinus ponderosa*. Very high charcoal accumulation rate peaks (greater than 35 pieces $\text{cm}^{-2}\ \text{yr}^{-1}$), much more than the concentrations recorded in the Fracas Lake area, occurred between the two events. Many charred *Picea* needles were found in the macrofossil assemblages, indicating that the fires occurred in *Picea* forest. Fire probably played an important role in local establishment of *Pinus ponderosa*. Fires could provide *Pinus ponderosa* with a competitive advantage (Habeck and Mutch, 1973; Kercher and Axelrod, 1984). After the fire(s), more areas were open where *Pinus ponderosa* was able to disperse seeds and germinate. At 9730 cal yr B.P., when the climate was suitable, *Pinus ponderosa* established quickly.

7.5. Early Holocene climate change and the Picea decline

With the establishment of *Pinus ponderosa* forest near Fracas Lake by ~11,000 cal yr B.P., *Picea* declined and disappeared very quickly (in less than 250 years). Near Bear Lake, however, *Picea* began to decline before the arrival of *Pinus ponderosa*, yet survived and persisted for thousands of years until modern times.

The difference in the decline of *Picea* in the two areas might indicate different climate warming patterns during the early Holocene. We assume that the general conditions when *Pinus ponderosa* first arrived at the two areas, i.e. Fracas Lake at ~10,995 cal yr B.P. and Bear Lake at ~9730 cal yr B.P., were similar. Temperature probably increased very rapidly at the beginning of the Holocene, and warming drove the lower and probably upper limits of *Picea* to higher elevations rapidly. However, after the establishment of *Pinus ponderosa* at Bear Lake, the warming rate probably decreased, and eventually temperature stabilized or fluctuated with low amplitude. The temperature and associated moisture stress never exceeded the suitable range for *Picea*. However, they may have exceeded the suitable range of *Picea engelmannii*, leading to replacement of *P. engelmannii* by *P. pungens* near Bear Lake. The temperature change pattern of rapid increase at the beginning of the Holocene followed by stabilization has been recorded in several areas around the world. Records from ice cores from Greenland (Dansgaard et al., 1989; Johnsen et al., 1992; Alley et al., 1993), Dunde, China (Thompson et al., 1989), and Huascaran, Peru (Thompson et al., 1995), coral records in the Southwest Pacific (Guilderson et al., 1994; Beck et al., 1997), pollen data in equatorial Africa (Bonnefille et al., 1990), and ostracod shell records from Lake Miragoane, Haiti (Hodell et al., 1991) all showed this pattern of rapid temperature increase at around 11,000 cal yr B.P. The warming rate ranged as high as 7ºC in about 50 years in South Greenland about 10,700 years ago, just after the younger Dryas (Dansgaard et al., 1989). These data suggest a possible global pattern of rapid warming. Our data suggest that southwestern North America may have experienced a similar pattern. On the Kaibab Plateau, after ~11,000 cal yr B.P., warming drove both *Picea* and *Pinus ponderosa* upward along the elevational gradient. The upward migration rates may have been faster at the beginning of the Holocene (~11,000 cal yr B.P.) when the temperature increased rapidly. This corresponds to the period when *Picea* disappeared from the Fracas Lake area. The migration was subsequently slowed by temperature stabilization, allowing *Picea* (mainly *P. pungens*) to persist in the Bear Lake area throughout the Holocene.

7.6. Paleoclimate history on the Kaibab Plateau

Late Glacial temperatures on the Kaibab Plateau were colder than today. Summer temperatures rose with increasing summer insolation in the Late Glacial. Though the Laurentide ice sheet was melting rapidly, it was still large enough to influence air circulation patterns (COHMAP, 1988; Kutzbach and Webb, 1993; Kutzbach et al., 1993). The westerlies were still south of their present position, bringing greater winter precipitation to the southwest United States than today. Meanwhile, higher summer insolation enhanced the southwest monsoon (COHMAP, 1988; Thompson et al., 1993), which brought more summer moisture from the Gulf of Mexico and the eastern Pacific Ocean. Both winter and summer precipitation were enhanced throughout the entire southwestern United States. Lake levels in the Great Basin were higher than today (Benson and Thompson, 1987; Thompson et al., 1993). Even in the Sonoran Desert of southwest Arizona, one of the driest areas in North America today, pinyon pine and juniper woodlands covered much of the region (Van Devender, 1977, 1987). However, during the Late Glacial, probably because the North American continent and the surrounding oceans were still cool, the difference of air pressures between the oceans and the continent was not very large, and so the southwest monsoon was probably weaker than in the early Holocene. High effective moisture during the Late Glacial was probably mainly from high winter and spring precipitation combined with cool temperature.

Temperature continued to rise in the early Holocene, but it was still cooler and wetter than today. Fracas Lake and Bear Lake were deepest during the early Holocene. The Jet Stream probably retreated northward slightly, and winter precipitation may have decreased a little. The moisture increase was probably mainly from increased summer precipitation, as the summer monsoon was presumably strongest during this period.

Beginning at ~8000 yr B.P., effective moisture began to decrease near Bear Lake, as indicated by the shallower water level and appearance of *Pseudotsuga menziesii*. The moisture change could be interpreted as the result of increased evaporation rates associated with increasing temperature. The Mid-Holocene was the warmest and driest period. Summer insolation was lower than during the Late Glacial and early Holocene, but still significantly higher than today (COHMAP, 1988; Thompson et al., 1993). The monsoon was probably stronger than today, and summer precipitation may have been also higher than today. However, high temperatures resulted in higher evaporation. Moreover, the Laurentide ice sheet had largely disappeared, and the Westerlies probably moved farther north, so winter precipitation might have declined further. The effective moisture on the Kaibab Plateau and the other high plateaus in northern Arizona and southern Utah decreased substantially. Some lakes dried out (e.g., Potato Lake), while others became much shallower (e.g., Fracas Lake). During the late Holocene, both the summer insolation and intensity of the summer monsoon decreased to near the modern level. Decreased temperatures brought higher effective moisture to the high plateau region, even though the summer monsoon may have been weaker than during the mid-Holocene. Southerly movement of the westerlies in winter after the mid-Holocene warm period may have brought more winter precipitation to this region. Strong El Niño events during the late Holocene may have also played a role in increased moisture (Ely et al., 1993).

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