The Geological Society of America
Special Paper 450
2009

A 19,000-year vegetation and climate record for Bear Lake, Utah and Idaho

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ABSTRACT

Pollen analysis of sediments from core BL96-2 at Bear Lake (42°N, 111°20′W), located on the Utah-Idaho border in America's western cordillera, provides a record of regional vegetation changes from full glacial to the late Holocene. The reconstructed vegetation records are mostly independent of Bear Lake's hydrologic state and are therefore useful for identifying times when climate forcing contributed to lake changes. The Bear Lake pollen results indicate that significant changes in the Bear Lake vegetation occurred during the intervals 15,300–13,900, 12,000–10,000, 7500–6700, 6700–5300, 3800–3600, and 2200–1300 cal yr B.P. These intervals coincide with regional shifts in vegetation and climate, documented in pollen, isotope and biogeographic records in the Basin and Range region, suggesting that large-scale climate was the primary forcing factor for these intervals of change. Maximum aridity and warmth is indicated from 12,000 to 7500 cal yr B.P., followed by intervals of generally more mesic and cool conditions, especially after 7500 cal yr B.P.

INTRODUCTION

Paleoenvironmental histories are often derived from multi-proxy studies of lake and wetland sediments. The aquatic environment tends to preserve characteristics in the sediments that are otherwise lost through oxidation or erosion. Deep lakes, in particular, can provide high-resolution records because of reduced wind-induced sediment mixing and profundal anoxia. Environmental proxies include diatoms, ostracodes, mollusks, oxygen and carbon isotopes, carbon content, particle-size, geochemistry, sedimentary magnetism, and pollen. In highly variable lake environments, the climatic signals of these proxies can be masked or confounded by internal forcing factors or strongly mitigated by within-lake environmental conditions. For example, in the past 19,000 years, Bear Lake's chemistry has varied widely as a result of changes in Bear River influx, resulting in relatively large magnitude changes in oxygen isotope ratios (Dean, this volume). The influence of temperature on these isotopic ratios is mixed with, and hidden by, these hydrologic events. Although pollen grains are subject to current-driven sorting and preservation conditions in the lake, most of the source area is terrestrial and dominantly extra-local, especially for large lakes (Tauber, 1977; Bradshaw, 1994; Jackson, 1994). Long-distance transport of pollen in river systems, or redeposition of pollen that has been exposed to an oxygenated environment, is easily distinguished from airborne, rapidly deposited pollen by its preservation state (Cushing, 1967). Pollen data can thus serve as a bellwether for distinguishing local-lake hydrologic changes from regional climate changes.

One of a series of papers in this volume examining Quaternary sediment records from Bear Lake, Utah and Idaho, this paper focuses on post-glacial vegetation reconstructions from

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Doner, L.A., 2009, A 19,000-year vegetation and climate record for Bear Lake, Utah and Idaho, *in* Rosenbaum, J.G., and Kaufman, D.S., eds., Paleoenvironments of Bear Lake, Utah and Idaho, and its catchment: Geological Society of America Special Paper 450, p. 213–223, doi: 10.1130/2009.2450(09). For permission to copy, contact editing@geosociety.org.

pollen analyses and identification of climate forcing of sedimentary changes. The overall aim of the Bear Lake project is to reconstruct local and regional changes associated with tectonic basin subsidence, Bear River migration, and climate change. Few continuous vegetation records from the glacial maximum to the late Holocene in the Basin and Range region of the western United States exist because of erosion of the long-term sediment record at low elevations from lake desiccation and at high elevations from mountain glaciations. Proximal to Bear Lake, pre-Holocene paleovegetation records have been developed from the Great Salt Lake/Bonneville Basin, covering the last 15 m.y. (Davis and Moutoux, 1998), from a 70,000 yr vegetation reconstruction in a modern marsh at Grays Lake, Idaho, ~80 km northeast of Bear Lake (Beiswenger, 1991), and from a deglacial sequence at Rapid Lake, Wyoming (Fall et al., 1995). Holocene records in the region also come from these records plus peat deposits in the Uinta Mountains, southeast of Bear Lake (Munroe, 2003). A new, multi-glacial pollen record from the GLAD800 drilling project at Bear Lake reveals regional vegetation sensitivity to summer insolation, global ice volume, and some Heinrich events (Jiménez-Moreno et al., 2007).

Although Bear Lake sediments show clear responses to the dominant climate changes of glacial-interglacial cycles and transition intervals (Jiménez-Moreno et al., 2007; Kaufman et al., this volume), interpretation of Bear Lake's response to the milder climate changes of the late Quaternary is complicated. Tectonic activity along the graben, diversion of the Bear River out of the lake watershed, and varying inputs from multiple groundwater sources caused strong variations in lake level and water source during the last 25 k.y. (Reheis et al., this volume). These hydrologic changes in the late Pleistocene confuse climate interpretations from diatoms, ostracodes, isotopes, and carbonates (Moser and Kimball, this volume; Bright, this volume, Chapter 8; Dean, this volume). Sedimentary magnetism also shows a strong glacial-interglacial component from transport of sediments to Bear Lake by the Bear River but after diversion of the river, this climate signal is lost by post-depositional destruction of Fe-oxide minerals (Rosenbaum and Heil, this volume). In this situation, where changes in water and sediment sources and chemistries create uncertainties in identification of forcing factors by alternative proxies, the onus to demonstrate climate forcing of late Quaternary changes in the sediments is on the pollen record.

SITE DESCRIPTION

Bear Lake (42°N, 111°20′W) occupies the southern reaches of Bear Lake Valley, a north-south oriented half-graben located between the Bear River Range to the west and the Bear Lake Plateau to the east (Fig. 1). The modern lake has a maximum elevation of 1805 m above sea level, constrained by the Lifton Bar, a natural beach barrier to the north, with a maximum lake extent of 32 km by 12 km, 282 km^2 surface area, and 63 m maximum depth (Birdsey, 1989). Dingle Swamp dominates the northern half of Bear Lake Valley and extends from Mud Lake, adjoining Lifton Bar, to the Bear River confluence with the Rainbow Canal. The lake today is fed primarily from spring-fed streams to the west, south, and east (Bright, this volume, Chapter 4). The Bear River has predominantly fed into the lake over the past 250 k.y., although this connection is periodically lost during warmer interglacial intervals (Kaufman et al., this volume). During the late Pleistocene, the lake was a maximum of 8 m above the modern level and the lake extent included the connection to the Bear River (Reheis et al., this volume).

Bear Lake's present climate is generally continental, with hot, dry summers, and winters cold enough to freeze the lake most years. Wind-blown ice accumulates in push ridges on the shores (Wurtsbaugh and Luecke, 1998) and probably contributes to the

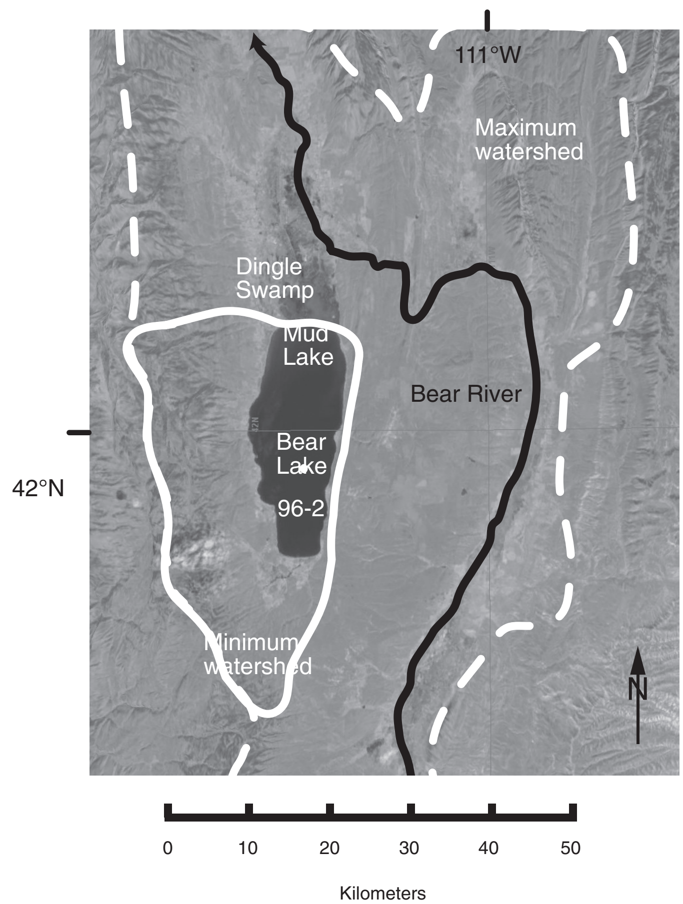

Figure 1. Satellite image of the Bear Lake region showing approximate boundaries of the Bear Lake watershed with Bear River influx (maximum) and without (minimum). The Bear River travels parallel to the lake on the far side of the eastern highlands, then turns sharply west and enters Dingle Swamp in the northern Bear Lake Valley. The swamp currently drains to the north, away from the lake. Prior to 1912, Mud Lake was isolated from Bear Lake by a barrier beach. At low lake levels, the lake is physically isolated from the swamp and the Bear River is not part of the lake's hydrology. At high lake levels, lake and swamp waters commingle and the Bear River's influence on the lake's hydrology is significant.

weakly vegetated lake margin. Bear Lake's climate differs from that of Great Salt Lake, ~120 km to the southwest, by Bear Lake's higher elevation and bounding ranges that create much larger orographic effects and potential for significant direct inputs from snowmelt. Although not well documented, evaporation potential at Bear Lake is expected to be much less than at Great Salt Lake because of cooler temperatures, topographic interference with wind patterns, and reduced hours of direct daylight (Kaliser, 1972; Amayreh, 1995). Because of these differences, Great Salt Lake and Bear Lake vegetation and paleoclimate records cannot be directly compared, although both should experience similar regional-scale trends in precipitation and drought that influence lake level and regional vegetation.

Modern vegetation around Bear Lake is mixed woodland, farmland, and rangeland. The valley is not heavily developed but is extensively farmed, beginning with settlement in the early 1800s. The native vegetation is dominated by shrubs, mostly sagebrush (*Artemisia* spp.) and juniper (*Juniperus* spp.) in the lower elevations of the watershed, with cottonwood (*Populus angustifolia* and *P. trichocarpa*) and willow (*Salix* spp.) near drainages. A mixed conifer forest dominates the upper elevations of the watershed, with lodgepole (*Pinus contorta*) and limber (*Pinus flexilis*) pine, Gambel oak (*Quercus gambelii*), maple (*Acer* spp.), Engelmann (*Picea engelmannii*) and blue (*Picea pungens*) spruce, and Douglas (*Psuedotsuga menziesii*), white (*Abies concolor*), and subalpine (*Abies lasiocarpa*) fir in the highlands. Government-sponsored Web sites provide GIS-based maps of modern vegetation distributions in the Bear Lake region (Albee et al., 1988; Thompson et al., 2000).

METHODS

One of three long sediment cores collected with a Kullenberg corer at Bear Lake in 1996, the 4-m-long BL96-2 core was determined by ^{14}C AMS (accelerator mass spectrometry) dating to have nearly complete representation of the Holocene (Colman et al., this volume). This core was subsampled for pollen analysis at irregular intervals, with closer intervals near lithologic changes. Pollen preparation followed standard techniques (Faegri and Iversen, 1989). Two tablets containing spores of *Lycopodium clavatum* from Lund University, batch 307862 with an average concentration of 13,500 ± 308 spores, were added to each sample to provide a control basis for concentration estimates. Prepared pollen samples are stored with glycerin in capped glass vials. Pollen keys and reference slides in collections kept by the U.S. Geological Survey (USGS) Earth Surface Processes Team in Denver, Colorado, aided in identification of unfamiliar grains (McAndrews et al., 1973; Heusser and Peteet, 1988; Faegri and Iversen, 1989; Moore et al., 1991).

Pollen identifications and counts were completed using an Olympus BH2 microscope with a combined ocular and dry-lens magnification factor of 500. Pollen reference collections at the USGS Earth Surface Processes Team (Denver) and the Institute of Arctic and Alpine Research, University of Colorado, aided identification of pollen types. USGS photographs and reference slides of pine pollen types were especially useful in recognizing species-specific variations in Quaternary and pre-Quaternary pollen morphology. Pine species were split out conservatively, with uncertain grains being grouped as diploxylon or haploxylon types, or as *Pinus*-type. To avoid problems of differential sorting, pollen grains were identified along a minimum of five evenly spaced transects, covering either half the slide from midline to outer edge, or the full slide, until a minimum of 300 grains were identified, excluding spores and aquatic types. The pollen types were grouped as trees, shrubs, herbs, aquatic, spores, and indeterminate. Indeterminate types were categorized as broken, corroded, crumpled, degraded, hidden, thinned and crumpled, or unknown, as suggested by Cushing (1967). Pollen percentages for each group were calculated relative to a total sum of trees, shrubs, herbs, and indeterminate types. Total pollen concentrations (in grains per gram of dry sediment) include all vascular pollen and spore types. Cyperaceae (sedges) in the western United States occur commonly as aquatic species and so were grouped as aquatic pollen. Pollen data calculations were completed in the program TILIA, version 2.0.b.4 (Grimm, 1990), with pollen diagrams from TILIAGRAPH, version 2.0.5.b (Grimm, 1998). Types with less than 1% maximum occurrence (rare types) are presented as numbers of grains rather than percentages.

The multivariate analysis program CONISS (Grimm, 1987) generated Euclidean-distance dissimilarity values for terrestrial pollen and spores with more than 1% maximum occurrence (Overpeck et al., 1985). Hierarchical, polythetic agglomerative dendrograms with minimum-variance clustering are used to indicate which samples are most alike (least dissimilar), with these appearing as tight clusters close to the axis. The distance off the axis (dissimilarity distance) provided an estimate of total sample variability and was useful in determining the relative differences between clusters (Gaugh, 1982). Because the presence and absence of sporadically occurring types is statistically weaker than for more abundant types, these rare types were excluded from the dissimilarity calculations. Horizontal "zone" lines indicate high dissimilarity between adjacent samples.

The age model used here is the polynomial ($y = 0.336 + 0.0379x + 2.83e^{-5}x^2$, $R^2 = 0.981$) that Colman et al. (this volume) fit to calibrated ^{14}C ages using the midpoints of 1σ intervals. Although the sampling resolution is low, the age basis for each of the samples is well constrained by this age model. The timing of intrasample changes is most accurately defined by the age of bounding samples. Thus, intervals of change in this record are designated by the two nearest neighbors.

RESULTS

Pollen counts were completed on 16 samples with identification of 110 pollen types, including 21 tree, 11 shrub, 58 herb, 9 spore, and 11 aquatic types. The pollen grains were generally well preserved and identifiable. Indeterminate pollen reached a maximum of 40% of the total pollen sum in the oldest sample, but after 15,500 cal yr B.P. was never more than 6.5%. Degraded and broken grains dominate the indeterminate fraction with hidden grains never more than 35% of this sub-sum.

All total pollen sums exceeded 400 grains, except in the two glacial samples that had pollen sums over 300 grains. Concentration values ranged from 5900 grains•g^{-1}, ca. 18,500 cal yr B.P., to 154,000 grains•g^{-1}, around 7000 cal yr B.P. A relatively large increase in concentration before 14,000 cal yr B.P. followed distinct decreases in indeterminate types. These results suggest that surface-transported pollen came from less distant sources, with less dilution of the pollen by sediment, by 15,500 cal yr B.P. Both of these changes are indicative of waning inputs of the Bear River's sediment load. Although herbaceous types dominate throughout the record, with herb:tree ratios of 1.1–2.6, periods of high total pollen concentration are generally associated with higher tree percentages. This is not true for the late Holocene, when the percentage of tree pollen was at a maximum but concentration was low. This concentration decrease in the uppermost sediments might result from increased dilution due to sedimentation rate increases. Alternatively, long-distance transport of tree pollen could enhance the representation of trees when local pollen inputs are low, such as occurs in alpine and arctic settings (Bourgeois, 1990; Fall, 1992; Markgraf, 1980).

In the dissimilarity analyses, 46 terrestrial pollen types with less than 1% maximum representation (rare types) were excluded, whereas ten rare types, originally identified to genus, were recategorized to genus-type or family to raise those representations above 1%. Dissimilarity analyses were run on 31 types, with nine identified to family, two to order, 15 to genera, and five to species (all *Pinus* spp.). Of these 31 types, 12 are tree types from six different genera. Four pollen zones, based on maximum dissimilarity values, are identified by hierarchical clustering with periods of greatest change in the pollen composition during the following intervals: 15,300–13,900, 12,000–10,000, 6700–5300, and 2200–1300 cal yr B.P. Maximum dissimilarity occurred during the deglacial interval (ca. 15,300–13,900 cal yr B.P.); the remaining clusters have progressively smaller difference values toward the present. Within-cluster dissimilarities are 50%–100% less than with their neighboring zones, with highest variability in within-cluster distances occurring prior to 10,000 cal yr B.P.

Relative percentages of the major pollen types, and raw counts of the rare types, are plotted in groups according their zone of maximum representation and shown with dissimilarity clustering results. These reveal a progression of dominant pollen types through time (Figs. 2 and 3). Most of the vegetation types identified, even those from the earliest parts of the record, occur in the Bear River watershed today (Albee et al., 1988; Burns and Honkala, 1990; Thompson et al., 2000; Welsh et al., 2003). The remaining non-local types occur within the neighboring regions of northern Arizona, southern Utah, and Wyoming. Their presence in the sediments of Bear Lake could be the result of long-distance pollen transport or biome shifts. The assemblages and proportional representation of these pollen types differ greatly over the last 19,000 cal yr, however, and these changes form the basis of the zone interpretations. All ages are rounded to the nearest 100 yr. Uncertainty in the timing of vegetation changes is high because of the low sampling resolution.

Zone 1 (19,000–15,300 cal yr B.P., full glacial) includes the full glacial and initial deglacial period. The most abundant pollen in this zone is sage (*Artemisia*). Pollen types reaching dominance in this interval are birch (*Betula*) and willow (*Salix*) and a variety of alpine meadow types common today in the Basin and Range. Families with steppe affiliations, such as Chenopodiaceae and Caryophyllaceae, are also well represented although they reach maxima later. Spruce (*Picea*), pine (*Pinus*), and fir (*Abies*) pollen occur in low abundances and may have grown vegetatively most of the time, producing pollen infrequently because of unfavorable climate conditions for reproduction. Spore types occurring in highest abundance here include ferns common to woodlands and rocky soils. These results are all consistent with the cold but generally ice-free environment associated with last glacial interval in the lower elevations of the Basin and Range region (Anderson et al., 1999; Barnosky et al., 1987; Benson et al., 1990; Madsen and Currey, 1979; Thompson et al., 1993).

Zone 2 (13,900–12,000 cal yr B.P., deglacial) includes the last stages of deglaciation and the Younger Dryas stage. This zone is defined by just two samples, so environmental responses are only coarsely resolved. Three species of pine, piñon (*P. edulis*), limber (*P. flexilis*), and ponderosa (*P. ponderosa*), reach their maxima in the interval, as do the rarer types poplar (*Populus*) and chestnut/chinquapin (*Castanea*). Many herbaceous types typical of woodlands and open forests occur in this zone, some reaching their maximum here. Percentages of sage and ragweed (*Ambrosia*), and other shrubs and herbs associated with arid steppe, are lower for both samples than in Zone 1. The pollen composition in this zone suggests an expansion of woodlands and mixed forests within the Bear Lake watershed.

Zone 3 (10,000–6700 cal yr B.P., early to middle Holocene) contains a rich tree assemblage with maximum percentages of juniper (Cupressaceae), Douglas fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), singleleaf piñon pine (*Pinus monophylla*), oak (*Quercus*), and maximum occurrences of the rare tree types of maple (*Acer*), ash (*Fraxinus*), and undifferentiated haploxylon pines. Alpine, woodland and wet meadow shrubs and herb types are also well represented in this zone, including alder (*Alnus*), Moschatel (*Adoxa*), *Dryas*, *Filipendula*, buckbean (*Menyanthes*), Saxifragaceae, and *Valeriana*. Steppe types increase as well, with maximum levels of sage, ragweed, shadbush (*Amelanchier*), goosefoot (Chenopodiaceae), pinks (Caryophyllaceae), and greasewood (*Sarcobatus*). There is a time-transgressive change in the pollen assemblage in this zone, with the dominant steppe plants, sage and ragweed, reaching their maxima before 8000 cal yr B.P. This is followed at 7500–7000 cal yr B.P., with maxima in tree and alpine types. This, in turn, is followed by a distinct assemblage comprising mostly Ponderosa and lodgepole pines, shadbush, sage, pinks, and greasewood ca. 6700 cal yr B.P.

Zone 4 (5300–2200 cal yr B.P., middle to late Holocene) has the highest percentages of the rose family (Rosaceae), followed

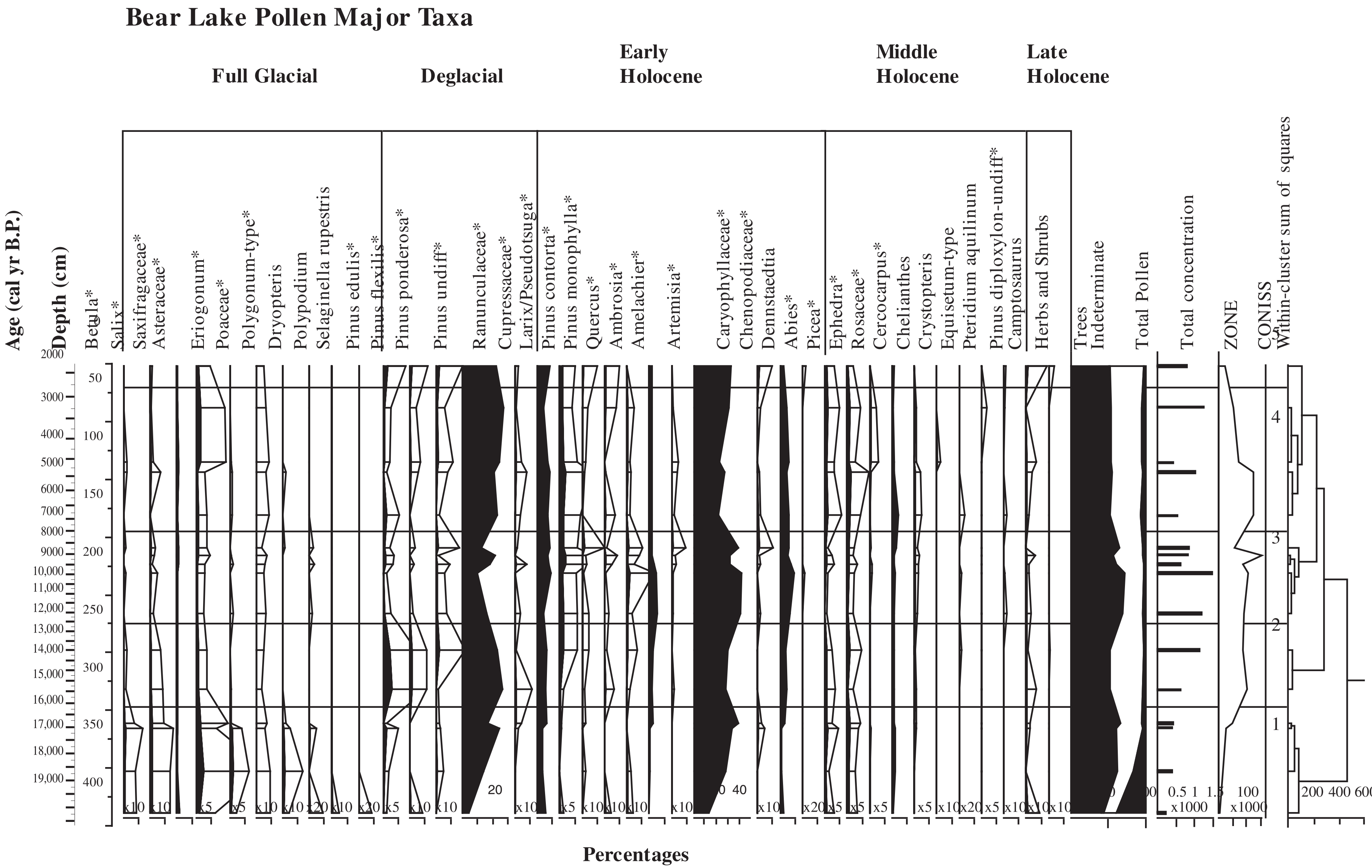

Figure 2. Major pollen taxa from the Bear Lake core 96-2, shown as percentages. Note that most of the x-axis curves are exaggerated by a factor of 5–20 (shown as hollow curves with histograms at sample points) and that the x-axis scaling (width) varies. Unexaggerated types are plotted as solid black curves. X-axis tick marks are every 10% with labels every 20%. Asterisks indicate pollen types used to create the CONISS dendrogram that, in turn, was used to define the zone boundaries (horizontal black lines). Pollen types are grouped according to the timing of their maximum zone values as dominant in the full glacial (before 15,300 cal yr B.P.), deglacial (ca. 13,900–12,000 cal yr B.P.), early Holocene (ca. 10,000–6700 cal yr B.P.), middle Holocene (ca. 5300–2200 cal yr B.P.), or late Holocene (1300 cal yr B.P.). Ages assigned to the pollen zone boundaries are approximations, calculated as the midpoints between the pollen samples in the neighboring zones.

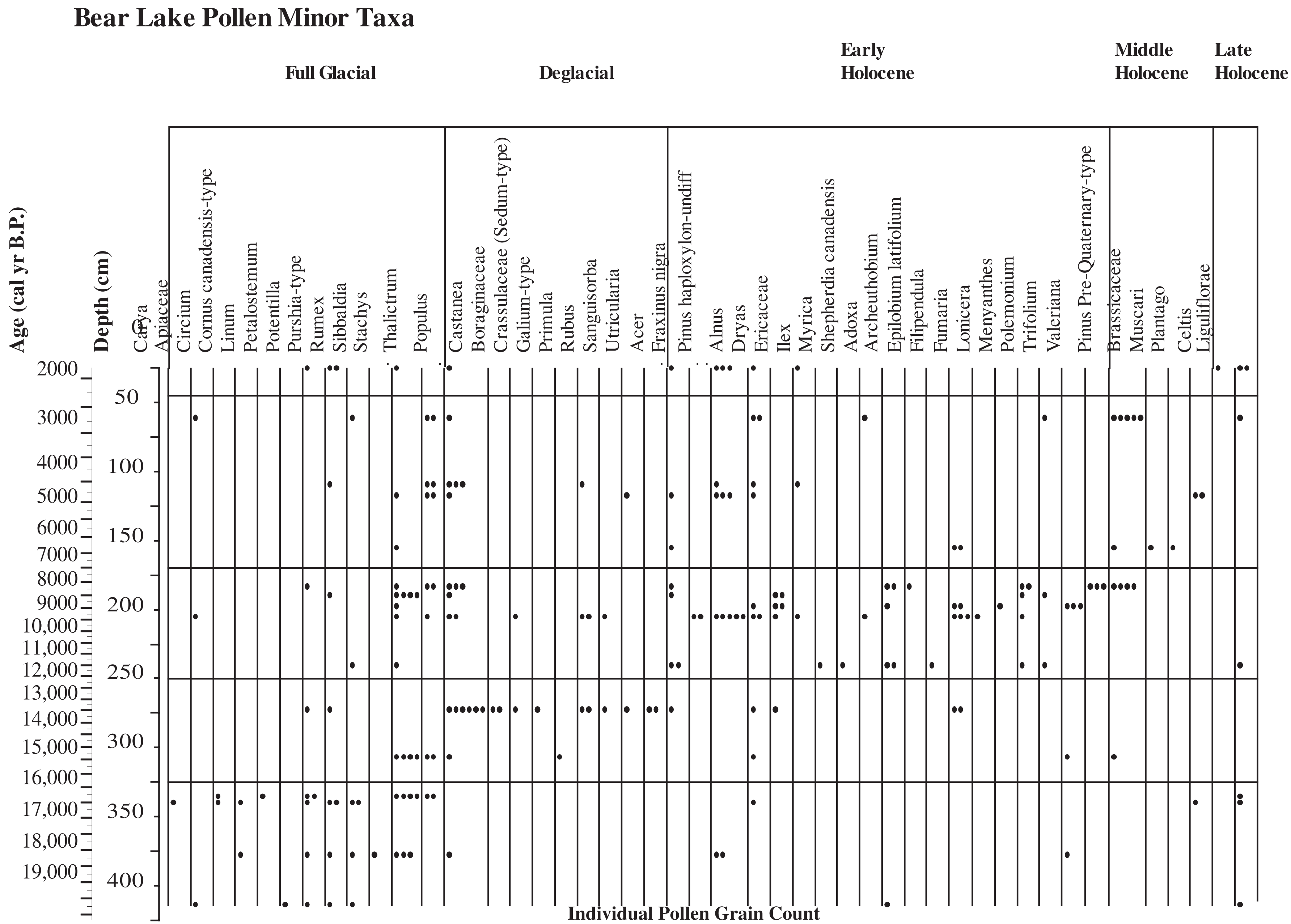

Figure 3. Minor (rare) pollen taxa from Bear Lake core BL96-2, shown as individual grain counts with one black dot per grain. Pollen types are grouped as in Figure 2. The horizontal zone lines are shown for reference although none of these rare types were included in the CONISS result.

by maximum values of the forest alpine types fir (*Abies*) and spruce (*Picea*), as well as mountain mahogany (*Cercocarpus*). Douglas fir and poplar continue to be relatively well represented in this zone. These moist forest types all reach maxima before 3800 cal yr B.P. After that, steppe and dry woodland types including pine, composites (Asteraceae), and Mormon tea (*Ephedra*) increase abruptly, while willow, buttercup (Ranunculaceae), and shadbush decrease (by 3600 cal yr B.P.). Total pollen concentration decreases by ~50% over this transition, but the pollen results offer no apparent explanation for this decrease. Moisture-loving horsetail (*Equisetum*) and pre-Quaternary pine types increase to their maxima ca. 2200 cal yr B.P., but decrease again after. These pre-Quaternary types, identified from pollen reference collections of Tertiary and Cretaceous pollen, indicate erosion and transport of pollen from sediments of these ages. The peak in pre-Quaternary types at the same time as peak aquatic types suggests an increase in precipitation leading to erosional down-cutting by streams tributary to the lake. Higher sediment inputs would cause pollen concentration decreases through dilution.

Zone 5 (ca. 1300 cal yr B.P., late Holocene) is defined by only one sample but it is distinct from the previous four samples of Zone 4. Upland types with maximum occurrence in this zone are the dandelion tribe (Liguliflorae) and three-needle pines (*Pinus* diploxylon). Pines of all identified types, except pre-Quaternary, and juniper increase slightly, while all the other tree types either decrease or remain at Zone 4 levels. Pinks and rose family types also increase. Many types present elsewhere in the core are not represented in this sample and only the oldest full-glacial sample has fewer types included in the CONISS statistics. Pollen concentration is lower than at any time since 16,350 cal yr B.P.

Amounts of aquatic pollen in sediments often correspond to changes in lake dimensions, including length of shoreline, and efficiency of pollen transport from shallow regions to the core site (Digerfeldt, 2003). The basin morphology of Bear Lake is such that increases in the size of Bear Lake beyond the Lifton Bar would greatly increase the habitat for rooting aquatic plants, providing an additional source of aquatic pollen to the core site during lake highstands. In the aquatic pollen types (Fig. 4), several distinct changes can be recognized. Because of their strong linkages with lake level, these aquatic pollen changes are detailed:

1. Between 19,000 and 15,500 cal yr B.P. the sedge family (Cyperaceae) reaches its greatest percentages. This sedge may be more tundra and cold meadow species than fully aquatic ones. Only two definitively aquatic types, pondweed (*Potamogeton natans*) and the green algae *Pediastrum*, occur during this interval.

2. Between ca. 15,500 and 15,400 cal yr B.P., sedges decrease by 50%, green algae increase and two new aquatic types, quillwort (*Isoetes)* and cattail (*Typha latifolia)* make their first occurrence in the record.

3. Circa 13,700 cal yr B.P., sedge is high again, but below pre-15,500 cal yr B.P. levels, and no other aquatic types occur besides green algae.

4. After 12,000 cal yr B.P., aquatic types become more diverse with simultaneous occurrence of sedges, cattail, pondweed and green algae. An interval of even higher aquatic diversification follows, with a maximum around 7800 cal yr B.P., with continuing representation by cattail, pondweed, and green algae and introduction of bur-reed (Sparganiaceae), duckweed (Lemnaceae), watermilfoil (*Myriophyllum alterniflorum*), water lily (*Nymphaea*), and arrowhead (*Sagittaria*).

5. Circa 7500 cal yr B.P., all but three aquatic types disappear. Sedge occurs at reduced levels, but one cattail species and green algae are distinctly higher in this sample. By 7000 cal yr B.P., this pattern is changed, with reduced levels of cattail and green algae but reappearance of pondweed. By 6700 cal yr B.P., cattail, sedge, and green algae are at local minima, and pondweed is the only other type represented.

6. At 5300 cal yr B.P., sedge and pondweed are relatively high and cattail and bur-reed reach maximum representation. Green algae are at their minimum at this time. Between 5300 and 3800 cal yr B.P., aquatic types are represented by green algae, sedge, cattail, and pondweed, but by 3500 cal yr B.P., only green algae and sedge occur.

7. Aquatic diversity remains low after 3500 cal yr B.P. with only cattail, sedge, and pondweed present at 2200 cal yr B.P. The youngest sample at 1300 cal yr B.P., is similarly depauperate, but contains the first occurrence of another cattail species (*T. angustifolium*), relatively strong representation by bur-reed, and low levels of sedge.

DISCUSSION

The Bear Lake paleovegetation record is largely in agreement with long-term regional paleoclimate reconstructions, many of which are based on pollen data. Records extending back several million years from sediments beneath modern Great Salt Lake (Davis and Moutoux, 1998), and 225 k.y. at Bear Lake (Jiménez-Moreno et al., 2007), indicate that sage-dominated steppe vegetation is regionally persistent over multiple glacial cycles, with increases in juniper, ragweed, and shadbush during interglacials, and in sage and conifers during glacials. Vegetation assemblages in the region are generally continuous through these glacial cycles, without the local extinctions that mark climate transitions along the tundra-forest boundary, for instance. Despite this, distinct climate-driven changes are identifiable at many sites by changes in relative abundances of steppe versus woodland/forest pollen (e.g., Thompson, 1990; Beiswenger, 1991; Fall et al., 1995; Davis and Moutoux, 1998; Quade et al., 1998; Munroe, 2003).

The most significant change in the Bear Lake pollen record, based on the Euclidean distances in the cluster analysis, is during deglaciation, the onset of which has been dated in various sites around the Great Basin between 17.5 and 16.0 ka (Licciardi et al., 2001. This deglacial interval has been tied to Heinrich Event 1 (Clark and Bartlein, 1995; Phillips et al., 1996). Although Heinrich events are thought to be cold periods with high moisture balance (Denton et al., 1999), Great Basin regional vegetation records indicate a trend toward warmer and moister conditions between 17,000 and 14,000 cal yr B.P. (Cole and Arundel, 2005;

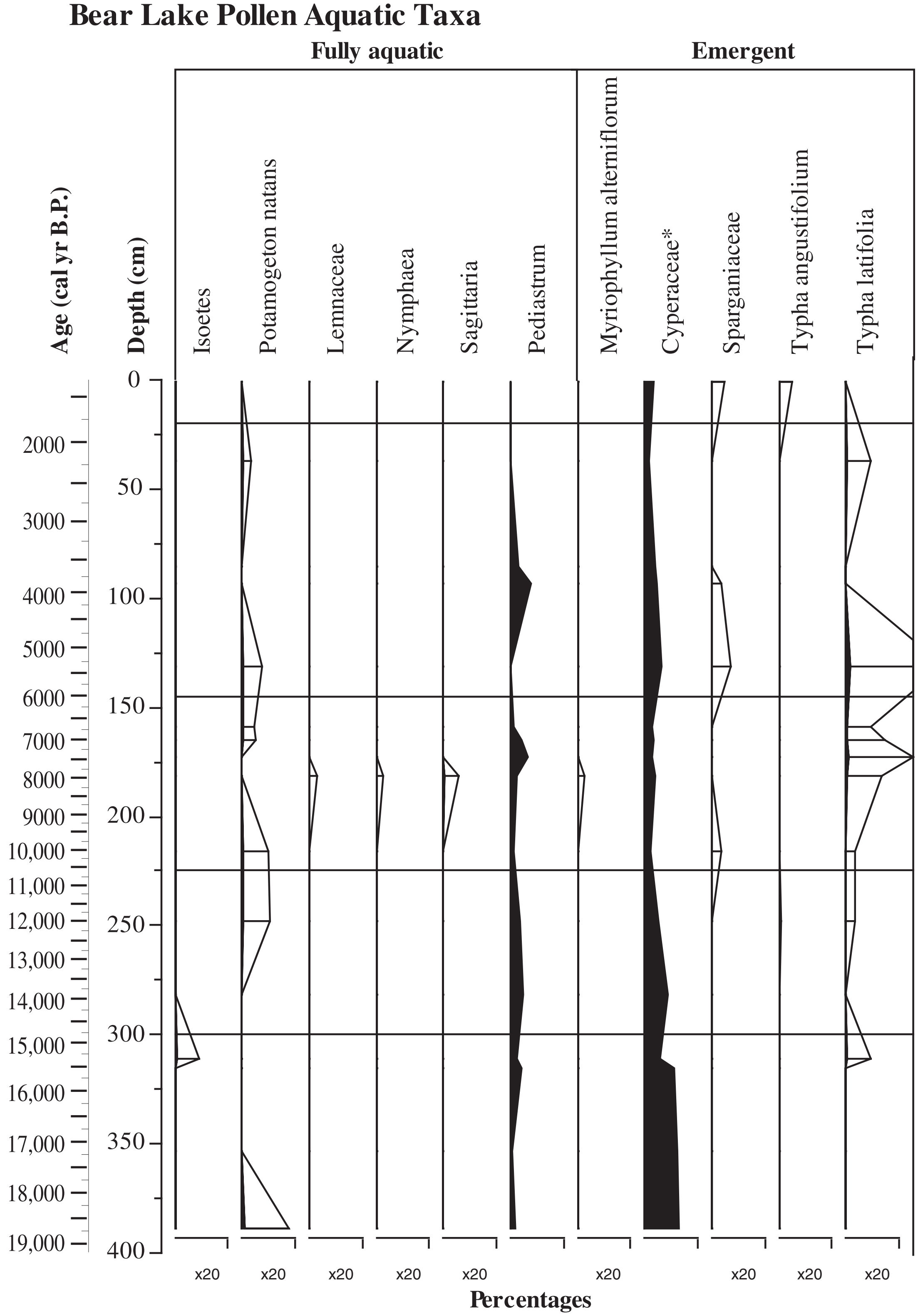

Figure 4. Aquatic pollen taxa from Bear Lake core BL96-2, shown as percentages. Tick marks and exaggeration are as in Figure 2. Horizontal zone lines are shown for reference although only one of these types (Cyperaceae) was included in the CONISS result. Cyperaceae (sedge) can occur as an upland plant in tundra biomes, or as an aquatic plant. Although its period of maximum representation is during the full glacial interval, it is shown here to highlight periods when the aquatic type might be present. The aquatic pollen are grouped into fully aquatic (submerged) and emergent types. Fully aquatic types can live in deep-water conditions (>20 m) if the water clarity is high, whereas emergent types live in shallow water (<3 m), along shorelines and in marshes.

Betancourt, 1990). Isotopes from northern Arizona packrat middens, and the biogeographic distribution of Utah agave found in the middens, indicate that minimum temperatures during this time were 1.5–3.5 °C warmer than before 17,000 yr B.P. (Cole and Arundel, 2005). Eolian records in the Canyonlands area suggest this warm and moist trend did not extend to the southeastern Colorado Plateau region (Reheis et al., 2005). At some time between 15,300 and 13,900 cal yr B.P., Bear Lake's vegetation switched from the cold-tolerant steppe/tundra plants that occurred in the full glacial interval to pine-woodland vegetation, agreeing in timing and level of response with the regional records but suggesting that the climate transition began after 15,300 cal yr B.P.

The deglacial vegetation at Bear Lake persisted from 13,900 to 12,000 cal yr B.P. The pine woodland vegetation of this period is consistent with regional records (Fall et al., 1995; Madsen et al., 2001). Although the Younger Dryas (ca. 12,900–11,600 cal yr B.P.) is documented in various records in western North America (Doerner and Carrera, 2001; Reasoner and Jodry, 2000; Polyak et al., 2004; Oviatt et al., 2005), it cannot be distinguished in the Bear Lake pollen data from the single sample located within the interval. Despite this, the second largest transition in the Bear Lake vegetation record overlaps part of the Younger Dryas, with the end of the deglacial and start of the early Holocene pollen zones (12,000 and 10,000 cal yr B.P.). Over this transition, conifers and cold-tolerant trees and herbs around Bear Lake gave way to sage-steppe plants.

Faunal data suggest that the early Holocene in the Great Basin region was moist and cool (Grayson, 2000; Madsen et al., 2001). Regional vegetation reconstructions are poorly dated for this interval, but mesic conditions are also suggested for Grays Lake, Idaho, by approx. 7900 cal yr B.P. (7100 ^{14}C yr B.P.) (Beiswenger, 1991) and for marsh deposits created by increased levels of Great Salt Lake, dated at 7650 ^{14}C yr B.P. (~8400 cal yr B.P.) (Murchison and Mulvey, 2000). Other records for the Great Basin also indicate greater effective moisture ca. 6400–6000 ^{14}C yr B.P. (7400–6800 cal yr B.P.) (summarized by Madsen et al., 2001). This interpretation of a cool, wet early Holocene is complicated by high-elevation vegetation records from the Uinta Mountains of northeastern Utah that indicate higher-than-modern temperatures by 9400 cal yr B.P. (Munroe, 2003), and by Grand Canyon midden records of Utah agave that suggest temperatures were above modern by 8500 cal yr B.P. (Cole and Arundel, 2005). In the Bear Lake record, the early Holocene interval is represented by just two samples, at 10,000 and 8000 cal yr B.P., in which sage reaches a maximum and tree pollen a minimum. Aquatic vegetation reaches highest diversity in the sample at 8000 cal yr B.P., suggesting that Bear Lake had a large extent of shallow water, consistent with flooding of the Bear Lake Valley. In the early Holocene pollen zone, diversity of plant types increases between 7500 and 6700 cal yr B.P. This high-diversity period includes an oscillation in vegetation (7500–7000 cal yr B.P.), with higher levels of cold-tolerant trees, shrubs, and herbs and green algae, while arid steppe plants, drought-tolerant trees, and emergent aquatic plants decreased. By the end of this oscillation, many types of pollen had returned to their earlier levels.

The Bear Lake vegetation changed to a conifer-dominated forest by 5300 cal yr B.P., with distinctly less sage and a wide variety of tree types. The vegetation then closely resembled that of the 7500–7000 cal yr B.P. oscillation, except that sage is lower in the post-5300 cal yr B.P. interval. Circa 3600 cal yr B.P. a smaller magnitude change occurred in the vegetation, with increased ponderosa pine, asters, poplar, and *Ephedra*, and decreased spruce, fir, willow and sage pollen. This is also seen in the 2200 cal yr B.P. sample. A return to cooler temperatures after 5000 cal yr B.P. is documented in other records with higher conifer representation at lower elevations, fauna consistent with cooler intervals, and increased levels of Great Salt Lake and Ruby Marsh (Madsen et al., 2001). The final transition in the Bear Lake vegetation record occurs between 2200 and 1300 cal yr B.P. Unfortunately the core-top is absent and the past 2000 yr is represented by only one sample. The vegetation represented in this sample differs from the middle Holocene ones in having a very low diversity and a higher proportion of pine. Pollen concentration in this sample is lower than in any other post-glacial sample.

Comparison of the Bear Lake vegetation record with other records from Bear Lake shows periods of concordance and discordance. The vegetation records support isotopic and magnetic indicators of Bear River influx and deglaciation after 17,000 cal yr B.P. (Rosenbaum and Heil, this volume). In addition, a sharp increase in $\delta^{18}O$ ca. 12,000 cal yr B.P., followed by an increase in Mg in endogenic calcite from 11,500 to 11,000 cal yr B.P. (Dean, this volume), coincides with the transition from deglacial to early Holocene vegetation. High lake levels postulated from isotope, diatom, and sedimentary records at 9000–7500 cal yr B.P. (Laabs and Kaufman, 2003; Dean, this volume; Moser and Kimball, this volume; Reheis et al., this volume; Smoot and Rosenbaum, this volume) are poorly resolved by the pollen record with samples only at 10,000 and 8000 cal yr B.P. The upland record in these two samples indicates arid conditions, with minima in tree types and maxima in steppe plants until 7500 cal yr B.P., yet the aquatic vegetation record concurs with a lake highstand interpretation at 8000 cal yr B.P. Following this evidence of a highstand, the maximum in tree vegetation between 7500 and 7000 cal yr B.P. suggests cooler, moister climates in the Bear Lake watershed. At the same time, a minor increase in quartz and magnetic susceptibility values in the Bear Lake sediments points to Bear River influences in the lake (Rosenbaum and Heil, this volume).

The offset in timing between the interpreted lake highstand in the lake geochemistry records (9000–7500 cal yr B.P.) and corroborating evidence in the upland pollen record (7500–7000 cal yr B.P.) is ~1000 yr. Although there is not sufficient data to explain the cause of this offset, it could be due to lags in overland transport of pollen from higher-elevation regions in the watershed to the lake. During periods of higher effective moisture, upland erosion may be minimized by vegetation cover. Vegetation die-offs in subsequent arid intervals would allow erosional downcutting that would transport both pollen and minerogenic matter to the lake. This hypothesis would also explain the increased influx of quartz at 7500–7000 cal yr B.P. It does not explain, however, why indeterminate and pre-Quaternary types, both indicators of erosional down-cutting, did not increase until the end of the tree-rich interval, at 6700 cal yr B.P. Alternatively, increased winter precipitation could create a highstand from 9000 to 7500 cal yr B.P. without significantly affecting upland vegetation if climate conditions during the growing season remained relatively dry. In the later Holocene, peaks in calcite mass accumulation rates and minor fluctuations in $\delta^{18}O$, ca. 4500–2800 cal yr B.P. (Dean et al., 2006), seem to be in phase with the 3800–3600 cal yr B.P. transition in the Bear Lake vegetation, and in regional vegetation records, toward cooler, more mesic conditions.

CONCLUSIONS

In summary, the Bear Lake vegetation record corresponds well, although with low temporal resolution, to regional records of change in vegetation and climate, documented in pollen, isotope, and biogeographic records in the Basin and Range region. Significant changes in the Bear Lake vegetation occurred during the intervals 15,300–13,900, 12,000–10,000, 7500–6700, 6700–5300, 3800–3600, and 2200–1300 cal yr B.P. All of these intervals, except for the last, fit within periods of change detected in other Bear Lake paleoenvironmental proxies, suggesting that those changes at Bear Lake were due to climatic forcing. In the pollen record, maximum aridity and warmth are indicated from 12,000 to 7500 cal yr B.P., but this is based on three samples separated by millennia. Data are insufficient to show whether the apparent aridity in the early Holocene was continuous or interrupted by a mesic interval, 9000–7500 cal yr B.P., as suggested by other Bear Lake environmental proxies, although aquatic pollen do support evidence of a highstand by 8000 cal yr B.P. The Bear Lake vegetation record indicates that several intervals change toward a more mesic and cool environment around the lake after 7500 cal yr B.P., compared to early Holocene conditions. The past 2000 yr are represented by only one sample, ca. 1300 cal. yr B.P., that is distinctly different from any other in the preceding 5000 years.

ACKNOWLEDGMENTS

The U.S. Geological Survey, Earth Surface Processes Team in Denver, Colorado, provided the samples, equipment, reference materials, and support services for this work, including helpful advice on the editing and scientific content.

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Manuscript Accepted by the Society 15 September 2008

Printed in the USA