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A ~13,000-year paleolimnological record from the Uinta Mountains, Utah, inferred from diatoms and loss-on-ignition analysis

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ABSTRACT

Paleolimnological research in mountainous regions of the Western United States provide baseline understanding of how these lake systems will respond to ongoing climate change. Fossil diatom assemblage and loss-on-ignition data were investigated from a ~13,000-year lake sediment core from the Uinta Mountains, northeastern Utah, USA. Results indicate the presence of three major zones of environmental change: 1) from ~12.9–10.9 cal ka, modern lake formation began, temperatures were cool, and water was turbid; 2) from ~10.9–3.5 cal ka conditions were warmer-than-present, and the lake stratified during the summer; and 3) beginning approximately 3.5 cal ka, temperatures decreased relative to the previous zone and the lake appears to have become increasingly alkaline. Shifts in diatom taxa relative abundances within the middle zone (ca. 8.2–6.5 and 5.0–3.5 cal ka) are probably caused by precipitation-driven decreases in alkalinity and increases in lake depth. This record reflects evolution of the lake system and suggests that currently rising temperatures will reduce ice cover and enhance lake stratification and internal nutrient cycling. Any future changes in precipitation patterns may also impact lake ecology through shifts in alkalinity and/or depth.

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1. Introduction

The Western United States, like most other parts of the globe, experienced statistically significant warming during the 20th century (e.g., IPCC, 2007). These recent temperature changes are impacting high altitude, aquatic ecosystems. For example, rising temperatures in some areas of North America and Europe have led to earlier ice-out times, enhanced lake stratification, a longer growing season, and greater nutrient cycling, which impact lake ecology (e.g., Winder and Schindler, 2004; Adrian et al., 2006; Rühland et al., 2008).

Understanding the sensitivity of high altitude, aquatic ecosystems to past variations in climate is important for anticipating future changes. Holocene paleolimnological records provide information about the evolution of lake systems and baseline conditions, including environmental variability and direction of change, that are useful for monitoring and restoration (e.g., Cohen, 2003; Kirilova et al., 2009). Changes observed in paleolimnological records during the Holocene Climatic Optimum (ca. 9.0–5.0 cal ka),

a time when global temperatures likely rose above modern values (e.g., Schönwiese, 1995; Huang et al., 2008), should provide insights into how freshwater ecosystems will respond to current warming trends, although antecedent conditions as well as rates and causes of change make this an imperfect analog for the future (e.g., Dwyer et al., 1996; Claussen et al., 2003).

Analysis of diatom species assemblage changes and loss-on-ignition (LOI) data in lake sediment cores can provide information about past environmental changes over seasonal timescales to hundreds of thousands of years. Diatoms are unicellular algae of the class Bacillariophyceae and exist in a wide range of wet or moist environments where there is sufficient light for photosynthesis. Changes in diatom species assemblages within a lake sediment core reflect past changes in environmental and hydrological conditions, because these algae are sensitive to a number of variables including temperature, pH, salinity, nutrient levels, lake levels, stratification and mixing (Battarbee, 1986; Bradbury, 1988; Smol, 1988; Psenner and Schmidt, 1992; Anderson, 2000; Moser et al., 1996; Gaedke et al., 1998; Lotter and Bigler, 2000; Rautio et al., 2000; Moser, 2004). LOI provides information on the organic and inorganic carbon fraction of lake sediments, from which inferences about climate changes, productivity in the lake and surrounding ecosystem,

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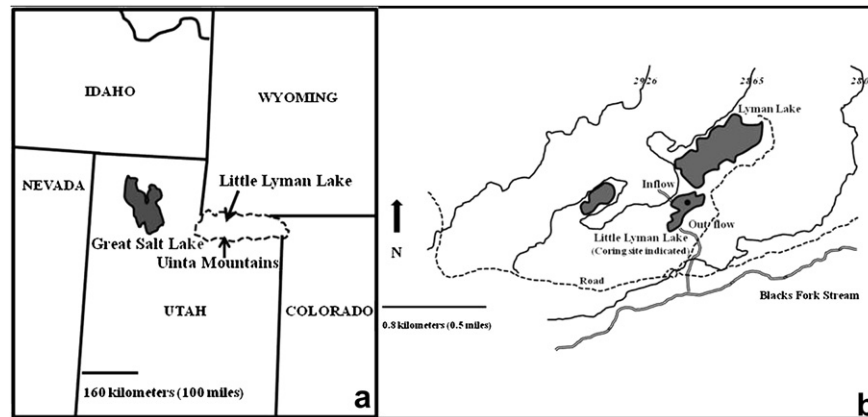


Fig. 1. Location of Little Lyman Lake in the Uinta Mountains, Utah (a) and close-up map of the area around the lake (b). Italicized numbers (e.g., 2926) refer to topographic contour lines in meters.

lake evolution, and catchment characteristics can be made (e.g., Dean, 1974; Mohr et al., 2000; Heiri et al., 2001).

The Uinta Mountains in northeastern Utah, USA, are an important conservation, recreation, and water resource area. This mountain range, which is part of the Upper Colorado River Basin, is approximately 150 km in length and features mountain peaks with elevations over 4000 m asl, alpine and subalpine lakes, numerous stream and river systems, and a range of moderate to high elevation ecosystems. The Uinta Mountains are protected public lands and are used for many kinds of outdoor recreation including hiking and fishing. Water originating here is an important resource within the state of Utah as well as for other Western U.S. states that use Colorado River water (Tingstad and MacDonald, 2010).

This research develops ~13,000-year diatom and LOI records from a lake sediment core from Little Lyman Lake in the Uinta Mountains, Utah. These data are used to identify a long-term environmental baseline for this region and to anticipate possible future changes.

2. Study area

Little Lyman Lake (LLL) is located in a carbonate basin at the lower tree-line along the northern flank of the Uinta Mountains ($40^{\circ} 56' 06''$ N, $110^{\circ} 36' 53''$ W) at an elevation of 2827 m asl (9276 f asl) (Fig. 1). The location of LLL in a mountainous area suggests that it may be sensitive to temperature and associated changes in nutrients (e.g., Rühland et al., 2008). Although LLL is an open system today, it may have been closed at times in the past. However, it would be difficult to use data from this lake to infer a complete range of climate-induced lake-level changes due to the presence of an outflow and the potential for groundwater flow from neighboring Lyman Lake. In addition, the LLL outflow is partially blocked by the remnants of a tie-hacking dam built in the 1800s for logging purposes. Table 1 lists some characteristics of this lake, which is weakly stratified in mid-summer, and relatively alkaline and saline compared with many other Uinta Mountain lakes.

The catchment surrounding LLL has a diverse vegetation assemblage including *Pinus contorta* Douglas (Lodgepole Pine), *Picea pungens* Engelm. (Blue Spruce), *Populus tremuloides* (Quaking Aspen),

Salix spp. (Willow family), *Artemisia tridentata* Nutt. (Great Basin Sagebrush), and a variety of wildflowers and herbs. The Uinta Mountains area experiences hot, dry summers along with cooler and somewhat wetter winters. Most precipitation is derived from winter Pacific frontal storms and summer thunderstorms related to North American Monsoon (NAM) activity (MacDonald and Tingstad, 2007). Average annual precipitation from 1971–2000 in the Uinta Mountains was 38–127 cm. Average maximum (minimum) temperatures were 3–17 (–13 to 3) °C (PRISM Climate Group, <http://www.prism.oregonstate.edu>, accessed July, 2009). Average April 1 snow-water equivalent (SWE) from 1986–2008 (the extent of available data) for the Hewinta Snowpack Telemetry site, which is located nearby LLL on the northern slope of the Uinta Mountains at a similar elevation, was 27.7 cm (10.9 in) (National Water and Climate Center, <http://www3.wcc.nrcs.usda.gov>, accessed September, 2009).

3. Materials and methods

In summer 2005, an 879-cm sediment core was retrieved from LLL in the Uinta Mountains (Fig. 1) using a modified Livingston piston corer (Livingstone, 1955). The LLL sediment core was kept cool, and was transported to UCLA where it was subsampled at 1-cm intervals. The core is largely composed of semi-regularly banded algal gyttja (individual bands are less than 0.25 cm in thickness), except for the base (874–879 cm), which is generally more silty, and the section from 867 to 873 cm, which is a fibrous, organic deposit. Ten terrestrial macrofossils were radiocarbon dated (Table 2) and calibrated using the program CALIB 5.0.2 (Stuiver and Reimer, 1993). Dates were assigned based on the midpoint of the highest probability 2-sigma range.

It is unclear why there are nearly identical dates at 315 and 518 cm, and date inversions elsewhere. All samples had sufficient carbon, the outer edges of the core were avoided for sampling, and there is no evidence of mass movement or turbation in the core. Because it could not be determined which dates were more accurate, all of the dates were included. These dates were used to construct a linear age model (Fig. 2), which may be more appropriate in this case than a polynomial model because of dating uncertainty.

Table 1
Modern environmental data for Little Lyman Lake.

Latitude	Longitude	Surface area (ha)	Catchment area (ha)	Surface temp. (°C)	Depth (m)	Secchi (m)	Spond (uS/cm)	Alkalinity (mg/L)
40.94°N	110.62°W	4.00	160.00	19.00	7.30	4.65	200.20	123.00

Table 2
Description of radiocarbon dates from the Little Lyman Lake sediment core.

Depth (cm)	Material (collected from core)	¹⁴ C date (years BP)	Error (years)	2-Sigma midpoint age (Cal. years BP)
46	Conifer needle	1925	15	1862
113	Conifer needle	930	20	854
154	Wood fragment	3880	25	4327
183	Conifer needle	3190	15	3413
315	Conifer needle	5215	15	5958
518	Wood fragment	5265	15	6006
640	Wood fragment	7575	20	8389
789	Wood fragment	9910	25	11300
841	Wood fragment	11360	25	13232
872	Charcoal and plant fragments	11150	33	13042

Diatom samples were processed at the University of Western Ontario using standard laboratory techniques as outlined in Battarbee (1986). Processing included the digestion of 1 cubic centimeter sediment samples in hydrochloric acid to remove carbonates and metal salts and oxides as well as the use of a concentrated 50:50 M solution of nitric and sulfuric acids to remove organic matter. Following chemical processing, diatom slurries were transferred to microscope coverslips, mounted onto microscope slides using Naphrax[®], and counted using fields of view in transects with a Leica microscope at a magnification of 1000 \times .

To examine large-scale, Holocene environmental change, 20-cm intervals were chosen for analysis of diatom species assemblage changes, which represents approximately 300 years. Diatom taxonomy primarily followed Krammer and Lange-Bertalot (1986–1991), Cumming et al. (1995), Bloom (2001), and Moser et al. (2004). Data for some taxa were grouped because similar and gradational morphological characteristics prevented distinct splitting among them in some samples. These included: *Cyclotella pseudostelligera*/*C. stelligera* (hereafter, *C. stelligera*), *C. radiosa* and *C. cf. radiosa* (*C. radiosa*), *Cymbella descripta*/*C. falaisensis*/*C. aff. descripta* & *falaisensis* (*C. descripta*), *C. minuta*/*C. silesiaca*/*C. aff. minuta* & *silesiaca* (*C. minuta*), *Fragilaria capucina* complex, and *Navicula cryptotenella*/*N. leptostriata* (*N. cryptotenella*).

Optimal sum of squares partitioning was used to zone diatom species assemblage data in the program ZONE 1.2 (Lotter and Juggins, 1991). The number of statistically significant zones was determined using the broken stick model (Bennett, 1996; Weckström et al., 2006). A Principal Components Analysis (PCA) of samples with species data square-root transformed was used to check optimal partitioning as well as suggest factors associated with major shifts in diatom species assemblage characteristics. PCA was performed using the program CANOCO (ter Braak and Šmilauer, 1998).

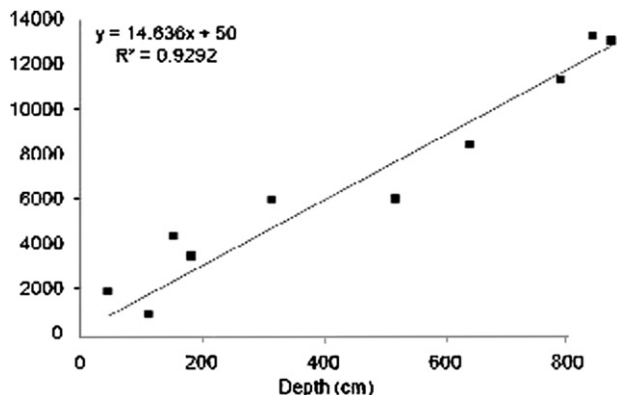


Fig. 2. Age-depth model for Little Lyman Lake. Ages in cal BP (vertical axis); depths in cm.

Diatom species diversity was measured using Hill's N2 statistic, which estimates the effective number of taxa in each sample (Hill, 1973; Rühland and Smol, 2005). Hill's N2 was calculated for each interval in the program C2 (Juggins, 2007). Increased diversity has been linked to warmer temperatures in situations where open water habitat is not considerably decreased as a result of desiccation. Warmer temperatures foster a longer growing season, enhanced stratification, and the establishment of more aquatic plants, which generate more diatom habitats (e.g., Karst-Riddoch et al., 2005; Antoniadou et al., 2007; Finkelstein and Gajewski, 2007).

The ratio of chrysophycean stomatocysts (classes Chrysophyceae and Synurophyceae; hereafter, chrysophytes or cysts) to the total number of diatoms in each sample was determined as $C/(C+(D/2)*100)$ (Smol, 1985). Changes in this ratio have been associated with temperature (e.g., Douglas and Smol, 1999; Catalan et al., 2002; Rühland and Smol, 2005), ice cover (e.g., Smol, 1983, 1988), trophic status (e.g., Smol, 1985; Moser et al., 2002; Michelutti et al., 2007), and salinity (e.g., Cumming et al., 1993). Cysts were not identified to lower taxonomic levels.

The dissolution index (F) was calculated for each sample, which is the proportion of pristine diatom valves in a sample relative to the total (modified from Ryves et al., 2001). F was determined by visual inspection during the process of identifying and counting valves. Highly alkaline conditions can lead to poor preservation through ionic dissociation of silicic acid (e.g., Flower, 1993; Karst-Riddoch et al., 2005; Finkelstein and Gajewski, 2007). More rapid burial of silica in lakes with high sedimentation rates tends to increase preservation in alkaline environments (Karst-Riddoch et al., 2005). Elevated salinity has also been associated with silica dissolution (e.g., Flower, 1993; Finkelstein and Gajewski, 2007). Other factors that can influence diatom preservation include temperature, water depth, and grazing or bioturbation (Flower, 1993; Stevens et al., 2006; Podritske and Gajewski, 2007).

LOI was performed at Middlebury College on samples taken at 1-cm intervals. A thermogravimetric analyzer determined both the organic (at 550 °C) and inorganic (at 1000 °C) carbon content of each sample after drying at 105 °C for 3 h.

4. Results and discussion

A total of 250 diatom species (33 genera) were identified in the 44 intervals counted. Only samples with a minimum of 550 counted valves (40 intervals) and species representing at least 2% of one sample (Table 3) were considered in the analysis.

Constrained optimal sum of squares partitioning indicated three statistically significant zones: 12.6–10.9 cal ka (Zone I: latest Pleistocene and Pleistocene/Holocene transition), 10.9–3.5 cal ka (Zone II: early and middle Holocene), and 3.5 cal ka-present (Zone III: late Holocene). This zonation is consistent with results of the PCA (Fig. 3a). Fig. 3b summarizes the relationships between diatom species and the first two PCA axes. The direction of each species vector indicates the relationship of the respective species with the axis, whereas vector length reflects the importance of each taxon in explaining variance along the axis.

PCA axis 1 explains 44.1% of the variance in the diatom data, and is related to temperature-driven changes in ice cover, growing season length, stratification, and nutrient cycling, and, to a lesser degree, shifts in water depth related to the evolution of LLL following the termination of the Last Glacial. Species with the strongest positive scores along this axis are small fragilarioid taxa. These benthic species are commonly characterized as pioneering taxa following the termination of the Last Glacial or major disturbances (e.g., Douglas et al., 1994; Weckström et al., 2006), and are adapted to cool, oligotrophic, and turbid conditions (e.g., Engstrom

Table 3
Diatom species (>2% in at least one sample) in the Little Lyman Lake sediment core.

Number	Taxon name	Authority
1	<i>Achnanthes minutissima</i>	Kütz.
2	<i>Amphora libyca</i>	Ehrenb.
3	<i>Asterionella formosa</i>	Hass.
4	<i>Brachysira vitrea</i>	(Grun.) Ross in Hartley
5	<i>Cocconeis placentula</i> var. <i>lineata</i>	(Ehrenb.) Van Heurck
6	<i>Cyclotella antiqua</i>	W. Sm.
7	<i>C. gamma</i>	Sovereign
8	<i>C. michiganiana</i>	Skvort.
9	<i>C. radiosa</i>	Grun.
10	<i>C. stelligera</i>	(Cleve & Grun. in Cleve) Van Heurck
11	<i>Cymbella cesatii</i>	(Rabenh.) Grun. in A. Schmidt
12	<i>C. cymbiformis</i> var. <i>nonpunctata</i>	Font.
13	<i>C. delicatula</i>	Kütz.
14	<i>C. descripta</i>	(Hust.) Lange-Bertalot
15	<i>C. lapponica</i>	Grun. Ex Cleve
16	<i>C. microcephala</i>	Grun. in Van Heurck
17	<i>C. minuta</i>	Hilse ex Rabenh.
18	<i>C. cf. PISCES</i> Sp. 1	Cumming et al. (1995)
19	<i>Denticula kuetzingii</i>	Grun.
20	<i>Diatom mesodon</i>	Kütz.
21	<i>Fragilaria capucina</i> complex	Desmazière
22	<i>F. crotonensis</i>	Kitt.
23	<i>F. nanana</i>	Lange-Bertalot
24	<i>F. tenera</i>	(W. Sm.) Lange-Bertalot
25	<i>Gomphonema angustum</i>	Agardh
26	<i>Mastogloia smithii</i> var. <i>lacustris</i>	Thwaites ex W. Sm.
27	<i>Navicula cryptocephala</i>	Kütz.
28	<i>N. cryptotenella</i>	Lange-Bertalot
29	<i>N. oblonga</i>	(Kütz.) Kütz.
30	<i>N. radiosa</i>	Kütz.
31	<i>Neidium ampliatum</i>	sensu Krammer & Lange-Bertalot
32	<i>Nitzschia fonticola</i>	Grun. In Van Heurck
33	<i>Pseudostaurosira brevistriata</i>	(Grun. in Van Heurck) D.M. Williams & Round
34	<i>Sellaphora pupula</i>	(Kütz.) Mereschk.
35	<i>Staurosira construens</i> var. <i>construens</i>	(Ehrenb.) Grun. D.M. Williams and Round
36	<i>S. construens</i> var. <i>venter</i>	(Ehrenb.) Grun. D.M. Williams and Round
37	<i>S. leptostauron</i>	(Ehrenb.) D.M. Williams and Round
38	<i>Staurosirella pinnata</i>	(Ehrenb.) D.M. Williams and Round
39	<i>Tabellaria flocculosa</i>	Köppen

et al., 1991; Karst-Riddoch et al., 2005; Finkelstein and Gajewski, 2007; Ampel et al., 2008). Most of the planktonic taxa found in the core have negative scores on axis 1, which probably reflects preferences for deeper water environments, reduced duration of ice cover, clearer water, a longer growing season, and enhanced stratification (e.g., Bakker and Vink, 1994; Lotter and Bigler, 2000; Karst-Riddoch et al., 2005; Rühland et al., 2008).

Axis 2 explains an additional 14.1% of the variance in the diatom data and may partly or wholly reflect changes in alkalinity and depth. Analysis of surface sediments and lake water chemistry from 61 lakes across the Uinta Mountains suggests that whereas *Asterionella formosa* (3), *Cyclotella pseudostelligera* (10), and *C. stelligera* (10), which display positive relationships with axis 2, have relatively low alkalinity optima (ranked 65th, 71st, and 75th, respectively, out of 85 diatom species included in the Weighted Averaging model with inverse deshrinking [$R_{boot}^2 = 0.778$; $RMSEP_{boot}$ as percentage of gradient = 14.4]), taxa which have negative correlations with axis 2, such as *Denticula kuetzingii* (19), *Cocconeis placentula* var. *lineata* (5), *Navicula cryptocephala* (32), *N. cryptotenella* (33), *N. pupula* (35), *N. radiosa* (36), *Cymbella minuta* (17), and *Tabellaria flocculosa* (39), may prefer more alkaline environments (ranked 4th, 5th, 9th, 14th, 28th, 32nd, 34th, and 43rd, respectively, out of 85 diatom species included in the Weighted Averaging procedure) (Tingstad, 2010; Tingstad et al., in preparation). Furthermore, the weakly positive correlation ($r = 0.24$, $p = 0.06$) of sample axis 2 scores with F-index values may imply a relationship between alkalinity and this axis because lower alkalinity can result in better preservation of diatom frustules (e.g., Flower, 1993).

Axis 2 may also partly reflect water depth. Planktonic and tychoplanktonic taxa such as *A. formosa* (3), *C. stelligera* (10), and *Fragilaria nanana* (27), which require deeper water environments for survival, have positive relationships with this axis. Two planktonic taxa that have negative scores along this axis, *Cyclotella gamma* (7) and *C. radiosa* (9), may tolerate more alkaline conditions than *A. formosa*, *C. stelligera*, and *F. nanana* (e.g., Philibert and Prairie, 2002; Bennion and Simpson, in press). However, PCA axis 2 cannot be clearly interpreted without additional analyses, such as carbon to nitrogen ratios and biogenic silica, which would provide more information about algal and diatom productivity (e.g., Wetzel, 2001; Cohen, 2003).

No attempt was made to interpret other PCA axes because they explained little additional variance in the diatom data (the eigenvalues for axes 3 and 4 were 0.084 and 0.060, respectively). Fig. 4

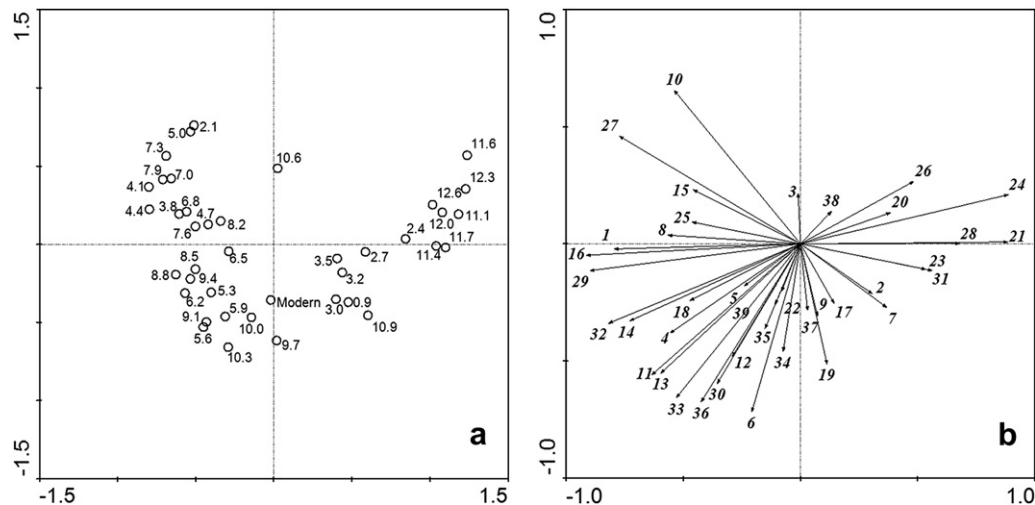


Fig. 3. Principal Components Analysis biplot (axes 1 and 2 explain 44.1% and 14.1% of variance in the diatom data, respectively) of sample (a) and selected species (b) scores from the Little Lyman Lake sediment core. Species numbers and names are shown in Table 3. Sample ages are labeled in cal years BP.

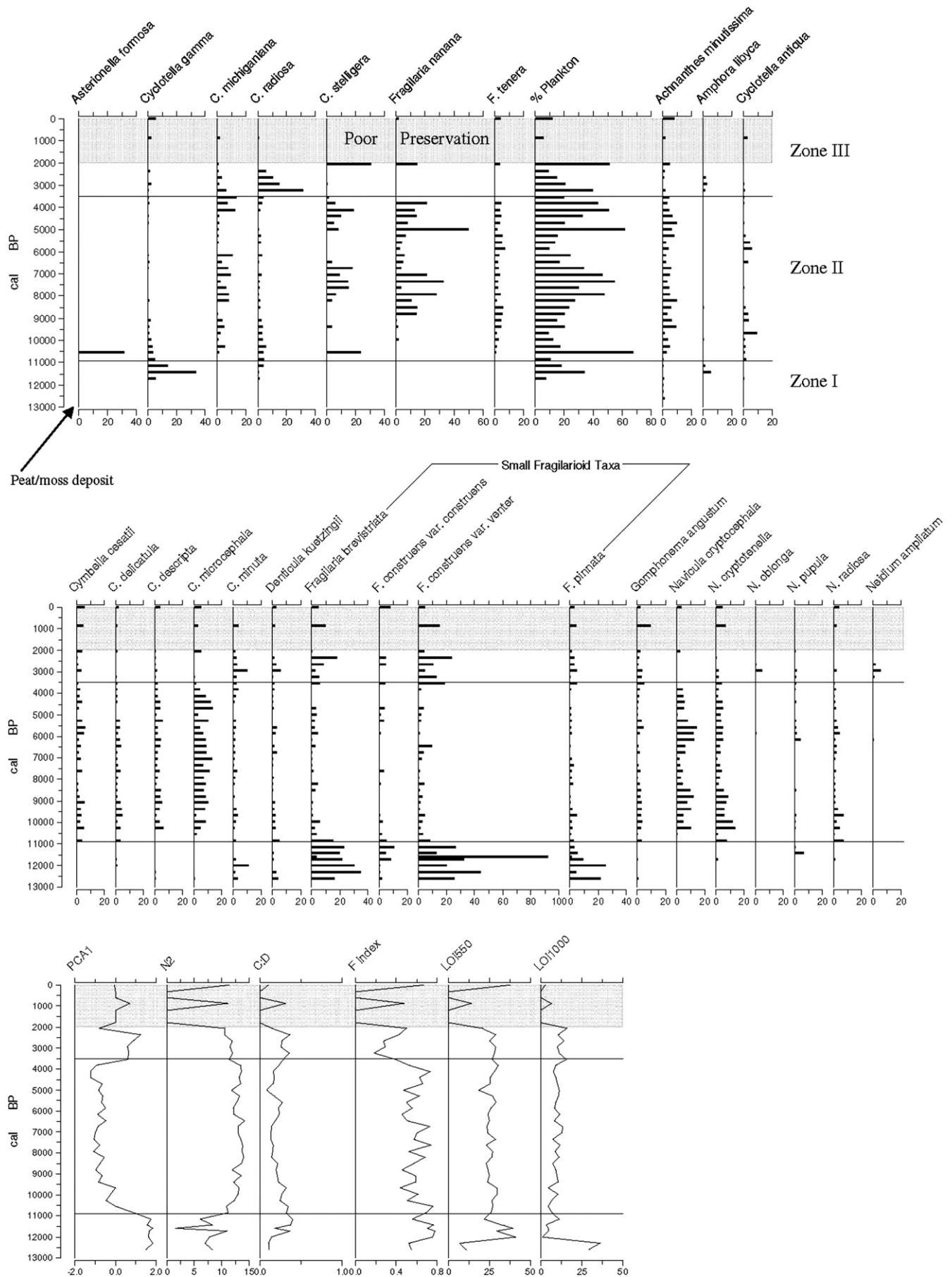


Fig. 4. Results of the lake sediment core analysis: diatom species assemblage data (only taxa with relative abundances >5%), PCA axis 1 scores, Hill's N2, C:D, F-index, LOI 550 (organic carbon), and LOI 1000 (inorganic carbon). *Fragilaria nanana* and *F. tenera* may be tychoplanktonic.

shows diatom species assemblage changes, PCA axis 1 scores, Hill's N2, C:D, F-index, LOI 550 (organic carbon), and LOI 1000 (inorganic carbon) in LLL over the last ~13.0 cal ka. *F. nanana* and *F. tenera* may be tycho planktonic (e.g., Kienel and Kumke, 2002), but are included in this stratigraphy with planktonic diatoms. Here, Zones I, II, and III are described in detail.

4.1. Zone I (12.9–10.9 cal ka)

No diatom valves were found at the very bottom of the core ~12.9 cal ka. There is no evidence of dissolved diatom frustules in this part of the core, or in the sediments directly above it, so the absence of diatoms is likely associated with lack of suitable diatom habitat. This absence of diatoms, along with the presence of inorganic sediments, indicates a cold, harsh environment. Due to colder temperatures, ice cover would have been prolonged, and the inputs of clastic material from a recently de-glaciated landscape would have been great, creating environments unfavorable for diatoms (e.g., Moser and Kimball, 2009; Bradshaw et al., 2000).

Between ~12.8 and 12.7 cal ka, an organic-rich layer with a peaty appearance was deposited. No diatoms were observed in this section, and this is interpreted as a period with low water levels, where no lake existed.

From ca. 12.6–12.0 cal ka, diatom assemblages are primarily characterized by *Fragilaria brevistriata*, *F. construens* var. *venter*, *F. construens* var. *construens*, and *F. pinnata*. The ratio of cysts to diatoms is low in the early part of this zone. Hill's N2 is also initially low and generally increases throughout this zone. Preservation is fairly good and organic carbon is elevated.

The dominance of these pioneering, benthic, small fragilarioid species and overall low diversity suggest that the present LLL began formation under cool, turbid, and lower-nutrient conditions. Although low C:D early in Zone I seems to contradict previous work suggesting that chrysophytes tend to thrive in cool, oligotrophic environments (e.g., Smol, 1985; Rautio et al., 2000; Catalan et al., 2002), these values could also reflect initially shallow water and/or absence of mosses (e.g., Douglas and Smol, 1995; Michelutti et al., 2007). In addition, it is possible that the small fragilarioid taxa may have been able to more effectively assimilate dissolved silica than chrysophytes under low-depth conditions because they can derive this nutrient from the sediment surface rather than from the water column (Engstrom et al., 1991).

Beginning ca. 12.0 cal ka, *Cyclotella gamma* has a high relative abundance in diatom assemblages otherwise dominated by small fragilarioid taxa. Although little is known about the ecology of this species, its close genetic relative, *C. meneghiniana* (Jung et al., 2010), is planktonic, is commonly found in rivers, can exist in low-light conditions, and may optimally grow under relatively warm temperatures (e.g., Lylis and Trainor, 1973; Shafik et al., 1997; Sayer and Roberts, 2001). Thus, the presence of *C. gamma* may imply that although conditions remained turbid, water depth and temperature were somewhat elevated compared with the earlier portion of Zone I. The appearance of *C. gamma* is also coincident with a rise in the relative number of cysts, which may track an increase in water depth, because many chrysophytes are planktonic, although periphytic taxa also exist (Douglas and Smol, 1995).

Around 11.6 cal ka, the diatom assemblage becomes dominated by *F. construens* var. *venter* (93%), Hill's N2 sharply decreases, C:D drops, and organic carbon peaks. This suggests cool, shallow conditions. Why *F. construens* var. *venter* is able to out-compete other small fragilarioid species is not clear, although the dominance of one taxon implies extreme environmental conditions (e.g., Antoniadou et al., 2007).

Whether environmental changes in Zone I are associated with the Younger Dryas stade (YD) (ca. 12.7 cal ka–11.5 cal ka) (e.g.,

Peteet, 1995; Alley, 2000) is not certain without a clearer chronology and the opportunity to analyze a longer environmental history. Generally cool temperatures and possible shifts in hydrology are consistent with the post-glacial history of this area (e.g., Munroe, 2002, 2005; Laabs and Carson, 2005). Paleoclimate work from elsewhere in the Western U.S. indicates that temperatures were considerably cooler than present during the YD (e.g., Madsen et al., 2001; Jiménez-Moreno et al., 2008; MacDonald et al., 2008), and that some areas within the Great Basin and Rocky Mountains were wetter (e.g., Thompson, 1992; Phillips et al., 1996; Gosse, 1995; Osborn et al., 1995; Menounos and Reasoner, 1997; Oviatt et al., 2005), whereas the Sierra Nevada, eastern California, Oregon, and other parts of the Great Basin may have experienced drier conditions (e.g., Benson et al., 1997; Clark and Gillespie, 1997; Llicardi, 2001; Madsen et al., 2001; James et al., 2002; Llicardi et al., 2004; Bacon et al., 2006). Some records seem to indicate that hydrological conditions changed from wetter to drier as the YD progressed (e.g., Thompson, 1992; Orme and Orme, 1993, 2008; Benson et al., 1997, 2002; Oviatt et al., 2005; MacDonald et al., 2008). The sudden dominance of *F. construens* var. *venter*, low Hill's N2, low C:D, and high sediment organic carbon values ~11.6 cal ka might reflect a brief period of cooler, more turbid, and possibly drier conditions marking the end of the YD.

4.2. Zone II (10.9–3.5 cal ka)

This zone is characterized by increases in *Achnanthes minutissima*, *Cymbella microcephala*, *Navicula cryptocephala*, and *N. cryptotenella*, as well as in planktonic taxa such as *Fragilaria nanana*, *Cyclotella stelligera*, and *C. michiganiana*, along with corresponding decreases in the relative abundances of small fragilarioid species. Throughout this zone, C:D values are lower, Hill's N2 values are stable and higher than in Zone I, and preservation is fairly good. Inorganic carbon content is relatively low, and organic content is lower and more stable than Zone I.

These data indicate warmer-than-present middle Holocene temperatures and the evolution of LLL into a more diverse, productive system. Specifically, the diatom assemblage implies shorter ice cover, a more extended growing season, earlier, longer, and/or deeper lake stratification as a result of warmer temperatures (Stoermer, 1977; Engstrom et al., 1991; Douglas et al., 1994; Van Dam et al., 1994; Gaedke et al., 1998; Lotter and Bigler, 2000; Bloom, 2001; Rühland and Smol, 2002, 2005; Sorvari et al., 2002; Baier et al., 2004; Karst-Riddoch et al., 2005; Weckström et al., 2006; Michelutti et al., 2007; Ampel et al., 2008; Rühland et al., 2008). Increases in *Cyclotella stelligera* and corresponding decreases in small fragilarioid species are similar to the response of several Northern Hemisphere lakes to recent rising global temperatures (Rühland et al., 2008). Decreases in the number of chrysophytes relative to diatoms may also reflect warmer conditions than in Zone I (e.g., Smol, 1985). Furthermore, the relatively large percentages of planktonic and tycho planktonic species suggest more deep-water habitat availability and/or greater transparency owing to deeper waters, longer ice-free periods or less turbid conditions. The presence of *Cyclotella stelligera*, *C. michiganiana*, *Fragilaria nanana*, *F. tenera*, *Cymbella microcephala*, *Navicula cryptocephala*, and *N. cryptotenella* may imply greater nutrient availability than in Zone I (e.g., Rühland and Smol, 2002; Baier et al., 2004; Gell et al., 2005). Enhanced internal nutrient cycling would occur if, compared with other zones, LLL was more deeply stratified in the summer.

Increases in the proportion of *F. nanana* and *C. stelligera* with corresponding decreases in somewhat more alkaliphilous taxa (*N. cryptocephala* and *N. cryptotenella* in particular) and *C. antiqua* from ca. 8.2–6.5 cal ka and 5.0–3.5 cal ka are probably related at least

partly to decreases in alkalinity and increases in depth, based on the interpretation of PCA axis 2. Relatively high F-index values also support decreased alkalinity, because diatom frustule preservation tends to increase with the reduced water column alkalinity (e.g., Flower, 1993), although elevated F-index values could also be related to an increase in production, which would have enhanced sedimentation rates and led to more rapid burial of diatom valves. Decreases in alkalinity could have resulted from enhanced freshwater inputs to the lake as well as decreases in carbonate-rich dust deposition or changes in internal lake processes.

Increases in the relative proportion of *C. michiganiana* and other planktonic/tychoplanktonic taxa during these periods would support an increase in water depth and corresponding decrease in alkalinity. Deeper water would likely increase the amount of open water habitats, favoring planktonic/tychoplanktonic species, and also decrease ionic concentration and alkalinity.

If the above shifts in diatom species assemblages are related to decreased alkalinity and/or increased lake depth, this record may suggest that precipitation increased during parts of the middle Holocene. Precipitation increases could have been related to enhanced winter snowpack and spring runoff, or to elevated rainfall in the summertime. However, the seasonality of the rainfall cannot be determined based on this record.

This is consistent with some previous work in the Western U.S. suggesting relatively moist conditions in the middle Holocene (Spaulding, 1991; Betancourt et al., 1993; Ely et al., 1993; Whitlock and Bartlein, 1993; Waters and Haynes, 2001; Poore et al., 2005; Anderson and Feiler, 2009; Moser and Kimball, 2009), and could be related to enhanced North American Monsoon activity as a result of increased seasonal differences in insolation. However, others have characterized the early and/or middle Holocene as a period of aridity in the western and central U.S. (Fritz et al., 1991; Laird et al., 1996; Bloom, 2007; Shuman et al., 2009), and there is still debate regarding the timing of increased monsoonal circulation (Barron et al., 2005).

4.3. Zone III (3.5 cal ka-present)

The late Holocene is characterized by increasing numbers of small fragilarioid species and *Cyclotella radiosa*, as well as declines in other taxa, *Navicula* and apically-elongated *Fragilaria* species in particular. Hill's N2 values are lower, suggesting a shift toward somewhat cooler conditions (e.g., Håkansson and Regnéll, 1993; Dixit and Smol, 1994; Lotter et al., 1998; Michelutti et al., 2007). F-index values are quite variable throughout this zone and some samples from the last 2000 years were uncountable due to poor silica preservation.

Changes in Zone III probably represent a cooling of temperatures and the development of an increasingly alkaline lake system. Extremely poor preservation over the last ~2000 years might also have been partly caused by dam blasting that took place in the area during the mid-1800s to float logs downstream. This may have disrupted upper sediments, exposing them to alkaline and saline water, although there is no visible evidence for this kind ofurbation in the sediment core. Low dissolved silica in the water column related to reductions in warm season precipitation and/or changes in vegetation may also partly explain the observed changes in preservation.

Interestingly, the position of the uppermost sample, representing modern conditions, on the PCA plot is closer to Zone II samples relative to other Zone III samples, indicating a recent change in diatom species assemblages towards something more similar to those from the mid-Holocene (Fig. 3a). This suggests that recent warming is shifting LLL back to conditions, such as increased productivity, more like those that existed in the mid-Holocene.

5. Conclusions

This research examined diatom species assemblage and LOI records from a lake sediment core in the Uinta Mountains, Utah. Modern lake formation began shortly after 13.0 cal ka, and conditions remained relatively cool, turbid, and nutrient-poor until around 10.9 cal ka. From ~10.9–3.5 cal ka, temperatures seem to have been elevated, and LLL became less ice-covered and perhaps deeper, resulting in the lake becoming stratified in the summertime. Periodic increases in the relative abundances of certain diatom taxa, particularly planktonic and tychoplanktonic taxa, within this zone may be related to decreases in alkalinity and/or increases in depth, which could have been driven by precipitation increases. Temperatures cooled somewhat starting ~3.5 cal ka. The Late Holocene is also characterized by increasingly alkaline conditions. Recently, LLL appears to be shifting back to conditions that were more similar to those in the mid-Holocene when temperatures were warmer.

This record describes the evolution of LLL and provides a long-term framework from which to examine environmental change in the Uinta Mountains. Although the mid-Holocene is an imperfect analog for future conditions, the data suggest that warmer temperatures may foster increased lake stratification and somewhat enhanced internal nutrient cycling in the future. Shifts in alkalinity may also be possible, especially if rising temperatures are accompanied by changes in precipitation patterns.

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