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Investigating the influence of hydrogeomorphic setting on the response of lake sedimentation to climatic changes in the Uinta Mountains, Utah, USA

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Abstract Reader Lake and Elbow Lake, two high-altitude lakes in the Uinta Mountains of Utah, are located approximately 2 km apart, at similar elevations, and within identical vegetation communities. Loss on ignition, carbon to nitrogen ratios, biogenic silica, and sediment grain size were analyzed throughout percussion cores retrieved from both lakes to construct continuous time series spanning 14 to ca. 2 ka BP. Given the proximity of the lakes, it is assumed that both were subjected to the same climatic forcing over this time. Accordingly, the first goal of this study was to consider these two multiproxy datasets in concert to yield an integrated paleoclimate record for this region. Close inspection of the records identified discrepancies indicating that the lakes responded to climate changes in different ways despite their proximity and similar setting. Clarifying these differences and understanding why the two lakes behaved differently at certain times was the second goal of this study. Overall, the paleoclimatic records document lake formation in the latest Pleistocene following glacier retreat. Buried glacier ice at the location of Reader Lake may have persisted through the Younger Dryas. Both lakes became biologically productive ca. 11.5 ka BP, and the first appearance of conifer needles indicates that trees had replaced alpine tundra in these watersheds by 10.5 ka BP. The interval from 10 to 6 ka BP was marked by a dramatic increase in precipitation, perhaps related to enhanced monsoonal circulation driven by the insolation maximum. The two lakes recorded this event in notably contrasting ways given their differing hydrogeomorphic settings. Precipitation decreased from 6 to 4 ka BP, and low water levels and drought conditions marked the interval from 4.0 to 2.7 ka BP. The integrated paleoclimate record developed from these cores provides a useful point of comparison with other records from the region. The differences between the records from these closely spaced lakes underscore the need to consider hydrogeomorphic setting when evaluating the suitability of a lake for a paleolimnological study.

Keywords Utah · Uinta Mountains · Lake sediment · Geomorphology · Drought · Precipitation · Holocene

Introduction

Multiproxy analysis of lacustrine sediment cores is a powerful method for creating paleoclimate reconstructions. Paleoenvironmental information can be extracted from sedimentary variables including

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diatom and chironomid assemblages (Stone and Fritz 2006; Porinchu et al. 2003), biogenic silica abundance (Blass et al. 2007), organic matter content (Munroe 2007), pollen grains (Mensing et al. 2004), charcoal abundance (Brunelle and Anderson 2003), sediment grain size (Noren et al. 2002), and geochemistry (Dean et al. 2002). Variation in these proxies is often interpreted as a sign of paleoclimatic change, and paleoclimate reconstructions from lake sediment records are valuable for developing and validating climate models.

Implicit in the process of developing paleoclimate reconstructions from lake sediment archives is the assumption that a target lake records past climate variability with fidelity. Yet it is also important to consider how the physical setting of a lake basin might impact the ability of sedimentary proxies to accurately record environmental changes. For example, Munroe (2007) investigated the relationship between hydrogeomorphology and loss-on-ignition (LOI) records, noting that lakes connected to high-volume inflows and outflows exhibited steady LOI records over time, while hydrologically closed basins featured more variable LOI. Similarly, in Sweden, Rubensdotter and Rosqvist (2003) reported considerable differences between cores retrieved from adjacent lakes and attributed this disagreement to minor differences in watershed geomorphology and the energy of sediment transport. More recently, Rubensdotter and Rosqvist (2009) concluded that fluvial input plays a critical role in determining the characteristics of lake sediment, especially in high-elevation environments where glacial sediment is abundant. These studies highlight the potential for erroneous paleoclimate interpretations if a core from a single lake is used to infer the history of an area without considering how hydrogeomorphic setting might filter the paleoclimate signal recorded in the proxies.

This study focuses on sediment cores retrieved from two high-elevation lakes in the Uinta Mountains of northeastern Utah (Fig. 1). Both lakes were formed in the latest Pleistocene following retreat of glaciers at the end of the last glaciation (Laabs et al. 2009). The two lakes are located at similar elevations and are surrounded by the same vegetation community. The lakes differ, however, in their geomorphic and

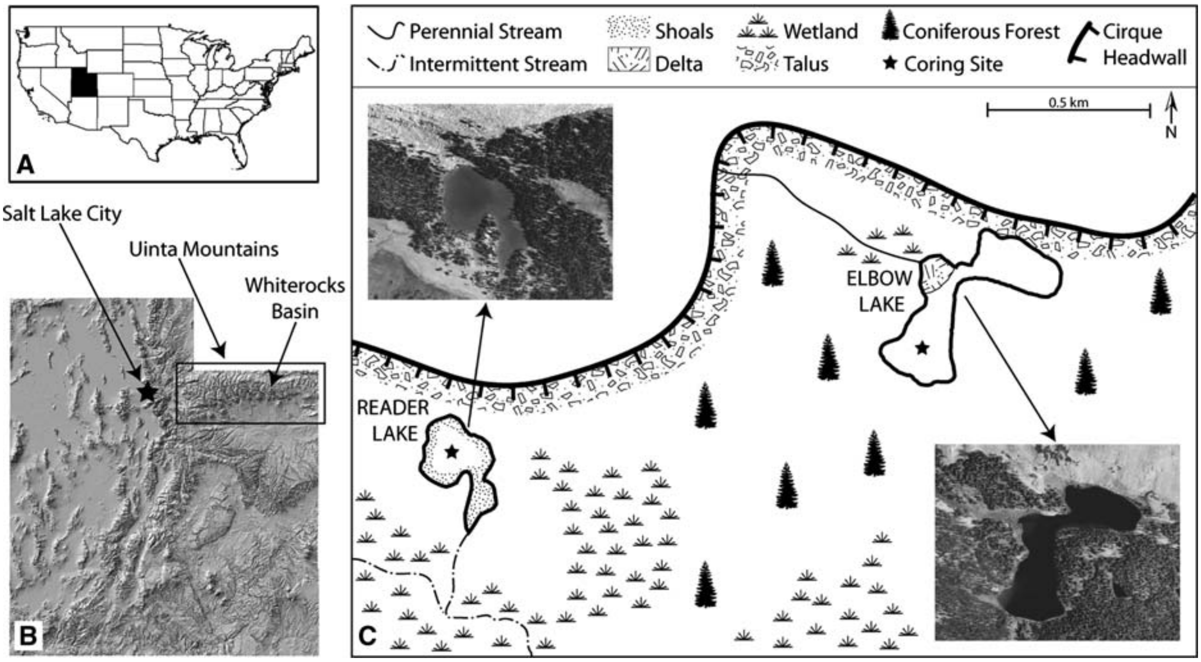


Fig. 1 *Panel A* Location of Utah in the western United States. *Panel B* Location of the Uinta Mountains in northeastern Utah. *Panel C* Geomorphic map of the study site. Reader Lake and Elbow Lake are less than 2 km apart at the same elevation. Reader Lake is a small, shallow kettle with an ephemeral outlet. The southeastern arm of the lake is a shoal less than 1 m deep. Elbow Lake is larger, deeper, and has an active inflow that has created a significant delta in the northwest corner of the lake

hydrologic settings. This study was designed to exploit these similarities and differences in order to (1) develop an integrated paleoclimate record for this region, and (2) explore how hydrogeomorphic setting impacts the way lake sediments record past climatic and environmental changes.

Study site

Geology and climate of the Uinta Mountains

The Uinta Mountains form the longest east–west trending range in the conterminous United States, stretching approximately 200 km across northeastern Utah (Fig. 1). The highest peaks rise to elevations over 4 km and support extensive areas of alpine tundra. The core of the range consists of a series of quartzite, shale, and sandstone layers that accumulated in a marine deltaic system 850–750 Ma and were uplifted during the Laramide orogeny (ca. 140–50 Ma; Dehler and Sprinkel 2005; Paulsen and Marshak 1999). No glaciers exist in the Uinta Mountains today, but abundant glacial features provide evidence for extensive glacierization during the Pleistocene. Munroe et al. (2006) and Laabs et al. (2009) concluded that the latest Pleistocene deglaciation began by 16 ka BP, and Munroe (2002) found that deglaciation was complete by 14–15 ka BP. Data from snowpack telemetry sites indicates that the mean annual air temperature at elevations above 3,100 m is below 0°C. Mean annual precipitation ranges from 500 to 925 mm per year at elevations of 2,650–3,300 m, with over 60% of the total annual precipitation falling as snow above 3,300 m (Munroe and Mickelson 2002).

Reader Lake and Elbow Lake

Reader Lake and Elbow Lake are located less than 2 km apart in the headwaters of the Whiterocks River in the southeastern Uinta Mountains (Fig. 1). Both lakes are surrounded by *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir) in a landscape of hummocky glacial deposits. A few small springs are present along the lake shorelines, but because the lakes are located near the highest elevations reached by the water table aquifer in the surficial deposits, it is likely that both lose water to the groundwater system.

Reader Lake (40°47′27″N, 100°03′37″W), at an elevation of 3,341 m, consists of a circular basin with a diameter of 200 m and a maximum depth of 4 m (Fig. 1, Table 1). The lake floor slopes gently away from shore before dropping steeply into the central basin. Appended to this basin is a shallow arm 200 m long and as narrow as 30 m wide, with a maximum depth of less than 2 m. The floor of this arm is stony, while the southern end contains a shelf of peat that is crossed by an ephemeral outlet carrying water only during the spring snowmelt. Bedrock ledges along the northern shore of the lake rise 100 m above the water surface and are partially mantled by coarse talus. Elsewhere the lake is bounded by hummocks of stony glacial till. A few small seeps enter the lake from the base of the northern ledges, and a dry channel leading to the northwestern corner appears to have been cut by snowmelt flowing from the talus. The lake's surface area is 4.8 ha and the watershed area is 54 ha, yielding a ratio of 11.3 (Table 1). Analysis of Landsat 5 imagery from July 1989 (Munroe unpublished) indicates that 26% of the watershed is forested, 29% is bedrock outcrop or talus, 27% is alpine tundra, 10% is wet meadow, and 8% is water.

Elbow Lake (40°47′37″N, 100°02′30″W), at an elevation of 3,326 m, has a more complex shape consisting of two elongate basins: a southern one oriented north–south, and an eastern one oriented east–west (Fig. 1). The southern basin is deeper, with a maximum depth of 10.7 m and steeply sloping eastern and western sides. The basins are partially

Table 1 Site parameters for Reader Lake and Elbow Lake

Lake						Watershed area		Watershed elevation		Watershed slope		
Lake name	Elevation (m)	Max depth (m)	Area A_L (ha)	Perimeter (m)	Complexity*	Area A_w (ha)	A_w/A_L	Mean (m)	Stdev (m)	Mean (deg)	Stdev (deg)	Aspect mean
Reader	3,341	4.0	4.8	1,179	1.52	54	11.3	3,387	64	11	10	194
Elbow	3,326	10.7	10.0	2,013	1.79	335	33.5	3,532	135	14	10	167

* Lake perimeter divided by circumference of a circle with the same area

separated by a bedrock shelf that crosses the lake in the narrow part of the elbow. A few springs are present at the southwestern end of the lake and a perennial inflowing stream draining an extensive wet meadow has formed a large delta in the northwestern corner. The northern shore is a steep talus mantled slope, rising more than 150 m above the water surface. Bedrock ledges are also present on the north side of the elbow. Other shores of the lake are bounded by uplands of hummocky glacial sediment with local relief less than 20 m. The area of the lake and the watershed are 10 and 335 ha, respectively, yielding a ratio (33.5) more than three times that of Reader Lake (Table 1). The overall watershed is higher (3,532 m) and steeper (14°) than that of Reader Lake (Table 1). In Landsat 5 imagery, 4% of the watershed is forested, 36% is bedrock outcrop and talus, 16% is alpine tundra, 38% is wet meadow, and 6% is covered by water or snow.

Methods

Sample collection and age control

Sediment cores were collected in July 2004 (Elbow Lake) and July 2005 (Reader Lake). Prior to coring, a bathymetric reconnaissance was conducted to identify the deepest part of each lake basin. Cores were collected from an anchored platform using a 7.6-cm diameter percussion corer (Reasoner 1993). Core barrels were driven until the point of refusal, and then recovered using a mechanical winch. Unfortunately, the uppermost sediment could not be retrieved in an undisturbed state with this method; however, the deeper, denser sediment was collected as a continuous core with minimal disturbance. After shipping, the cores were stored at 5°C until analyzed. For sampling, cores were split lengthwise into two halves; one half was wet-sieved in 1-cm slices at 500 μm to separate material suitable for radiocarbon dating. The other half was divided into four 3-cm^3 samples at 1-cm intervals.

Macrofossils and pollen concentrates were sent to the University of Arizona AMS Laboratory and the Woods Hole NOSAMS Facility for AMS radiocarbon dating. Pollen concentrates were prepared following Brown et al. (1989). Samples were visually examined under magnification to evaluate purity of the concentrate before submission, and although the pollen was not investigated quantitatively, the vast majority of the grains were of the genus *Pinus*. Eight samples from Reader Lake and seven samples from Elbow Lake were dated (Table 2). Radiocarbon ages were calibrated with Calib 5.0. The midpoints of the 2-sigma calibration ranges were plotted against depth, and a depth-age model was developed by fitting a cubic spline to the datapoints (Fig. 2). All ages are reported in thousands of calendar years before A.D. 1950, hereafter denoted "ka BP".

Sample analysis

Four proxies were utilized in this study: loss-on-ignition (LOI), carbon to nitrogen (C/N) ratios, biogenic silica content (bSi), and sediment grain size (GS). As described by Dean (1974), LOI determines the weight-percent of organic matter of each sample and serves as a proxy for total organic productivity both in and around the lake. C/N ratios quantify the relative abundance of terrestrially and aquatically derived organic material in the sediment, with a higher C/N characteristic of a more terrestrial source (Meyers and Ishiwatari 1993; Sampei and Matsumoto 2001). The bSi analysis quantifies the abundance of diatoms and other siliceous aquatic organisms and serves as a proxy for primary productivity within the lake (DeMaster 1981; Peinerud et al. 2001). The mean GS of processed samples provides information about terrestrially derived clastic material and is useful for identifying changes in the energy of inflowing water (Noren et al. 2002).

Samples taken from the two cores were analyzed at 1-cm intervals for LOI, C/N and bSi, and at a 2-cm interval for GS. LOI analysis was performed on a Leco TGA-701 thermogravimetric analyzer. Samples were heated to 105°C for 4 h under a 100% N_2 atmosphere to determine water content, then to 550°C for 3 h under ambient atmosphere to determine organic matter content. Empirical testing reveals that LOI measurements made on separate samples from the same stratigraphic level have a standard deviation of 8%, while instrument error for this method is ±3%. C/N analysis was performed on a CE Instruments NC 2500 elemental analyzer. The precision of the analyzer is approximately 1% for C and 0.5% for N. Samples were analyzed for bSi with a method adapted from DeMaster (1981) and Mucciarone (2003) that involved hourly extractions during a 5 h

Table 2 Radiocarbon results for Reader Lake and Elbow Lake

Lake name	Lab #	Depth	Material	d13C	^{14}C age	+/−	Midpoint*	Range**
Reader	OS-54821	32	Misc	−25.23	1,820	80	1,737	183
Reader	OS-53964	106.5	Conifer needle	−25.32	4,660	55	5,391	94
Reader	OS-54188	150.5	Conifer needle	−26.11	7,860	65	8,678	140
Reader	OS-55206	219	Pollen concentrate	−25.78	9,700	70	10,882	97
Reader	OS-54085	220.5	Conifer needle	−23.18	9,560	60	10,919	218
Reader	OS-55443	239	*Daphnia* ephippia	−25.9	10,150	55	11,827	226
Reader	OS-55187	239	Pollen concentrate	−25.33	10,400	50	12,240	163
Reader	OS-54031	244	Pollen concentrate	−24.73	9,460	60	10,714	158
Elbow	AA-62734	30.5	*Daphnia* ephippia	−27.89	3,218	40	3,427	62.5
Elbow	AA-62735	96.5	Conifer needle	−23.4	5,863	44	6,675	113
Elbow	OS-54192	127.5	Conifer needle	−22.69	8,270	55	9,261	171.5
Elbow	AA-62736	142.5	Conifer needle	−26.43	9,188	54	10,369	128.5
Elbow	OS-54166	153.5	*Daphnia* ephippia	−27.54	10,050	60	11,566	259
Elbow	OS-54306	153.5	Pollen concentrate	−26.2	9,280	65	10,428	170
Elbow	AA-62737	216.5	*Daphnia* ephippia	−18.38	12,068	72	13,927	155.5

* Midpoint of 2-sigma calibration range determined with Calib 5.0

** 2-sigma age range in calender years

leach in 0.1 M NaOH to differentiate between mineral and biogenic SiO_2. At the end of the leach, a sequence of reagents was added to create a blue color development that was read in a Hitachi U-2001 spectrophotometer against a 10-sample standard curve. The precision of bSi measurements was determined to be ±10% through analysis of replicates. GS samples were treated with 35% H_2O_2 and 0.1 M NaOH to dissolve organic matter and diatoms, respectively, before analysis in a Horiba LA-950 laser scattering particle size analyzer. All time series were smoothed with a Gaussian filter to facilitate identification of long-term trends. The Gaussian filter used a 1-sigma width of ±3 samples. Given the average sample spacing of about 50 years through these time series, the full width of the smoothing region is about 300 years.

Results

Stratigraphy

The cores from Reader Lake and Elbow Lake record continuous sedimentation with no evidence of unconformities or disturbances related to coring. The core retrieved from Reader Lake is 245 cm long (Fig. 2). The bottom 6 cm penetrated into dense sandy gravel. This unit is overlain by 25 cm of dense, reddish brown (5YR 4/3) silty clay with mm-scale mottling that transitions upward into more obvious mm-scale layering. From a depth of 194–170 cm, the mm-scale laminations become darker brown (7.5YR 3/2) before grading into a uniform very dark gray (2.5YR 3/1) gyttja that continues to a depth of 100 cm. Above 100 cm the gyttja remains very dark but with somewhat yellower hues (7.5YR or 10YR). Between 84 and 63 cm the sediment alternates between black (10YR 2/1) and slightly redder-black (7.5YR 2/1). This change, which occurs three times, is visually more distinct than the Munsell color designations suggest, and is accompanied by a shift from algal gyttja to humified peat. This interval ends at a depth of 63 cm, and from there upward the core is a massive very dark gray (7.5YR 3/1) gyttja.

The bottom 68 cm of the 216 cm core retrieved from Elbow Lake are primarily a heavy, reddish brown (2.5YR 5/3) silty clay (Fig. 2). Between 211 and 193 cm this silty clay is interrupted by three graded beds of dense silt overlain by nearly pure clay. The lowest of these layers (from 211 to 210 cm) is the thinnest, while the upper one (from 198 to 193 cm) is the thickest. *Daphnia* ephippia are distributed throughout the sediment from the core

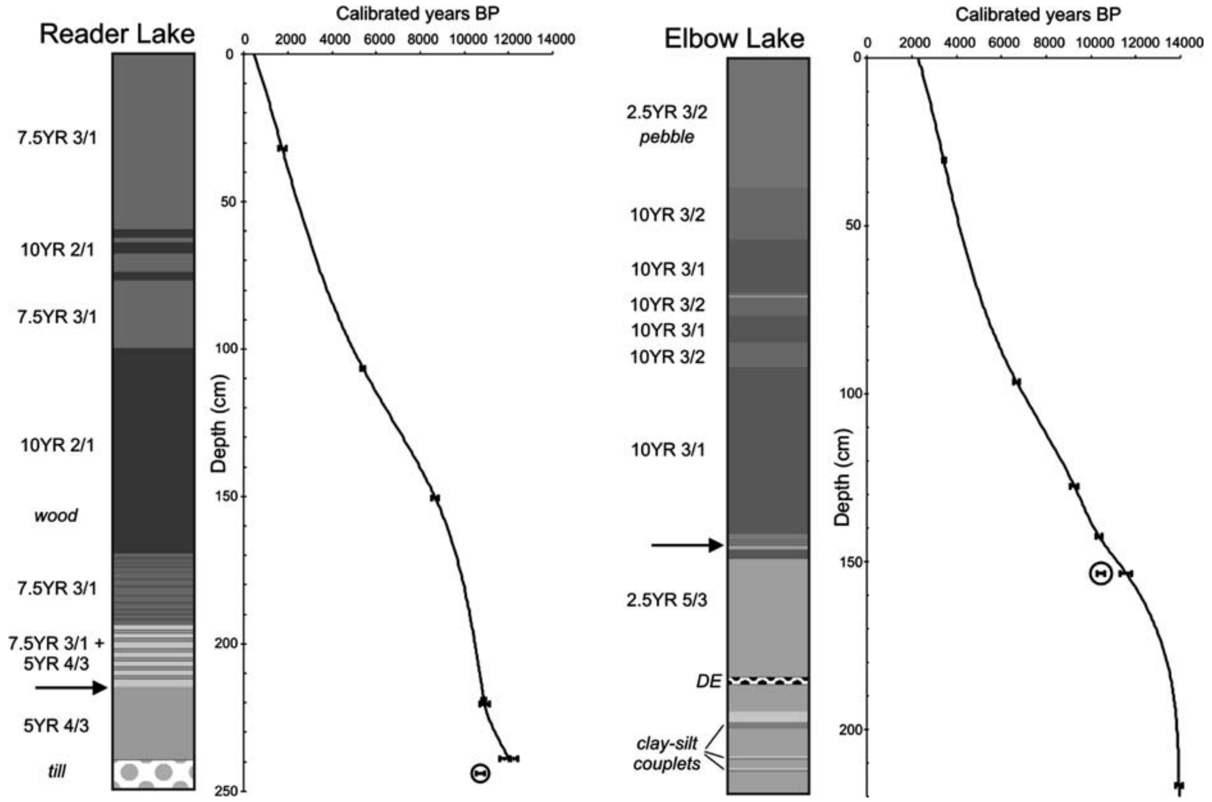


Fig. 2 Stratigraphic columns, radiocarbon age-control, and depth-age models for Reader Lake and Elbow Lake. Munsell color designations are given for major stratigraphic layers, and the *arrow* marks the visual transition between inorganic and organic sediment. "DE" is *Daphnia* ephippia. Age-control is presented as the midpoint of the 2-sigma calibration range for each AMS ^{14}C date. *Error bars* represent the width of the 2-sigma calibration range having the largest probability. Age-models were determined as a cubic spline fit to the calibrated ages; *encircled datapoints* were ignored in the age-model (see text for details)

bottom to a depth of 161 cm, and are particularly dense from 185 to 182 cm where they form an obvious black layer. Between 161 and 148 cm the sediment remains a heavy, reddish brown (2.5YR 5/3) silty clay, but *Daphnia* ephippia are absent. At a depth of 148 cm a series of prominent oscillations begins between the silty clay found below and a very dark gray (10YR 3/1) silty gyttja that dominates the upper 140 cm. The interval from 144 to 140 cm is particularly striking with mm-scale interbeds of reddish and dark gray sediment. The section from 143 to 142 cm contained over 20 conifer needles. From 140 to 38 cm the core features subdued alternations between very dark gray (10YR 3/2) and black (10YR 2/1) massive silty gyttja with few notable features. The uppermost 38 cm is a massive, redder (2.5YR 3/2) gyttja.

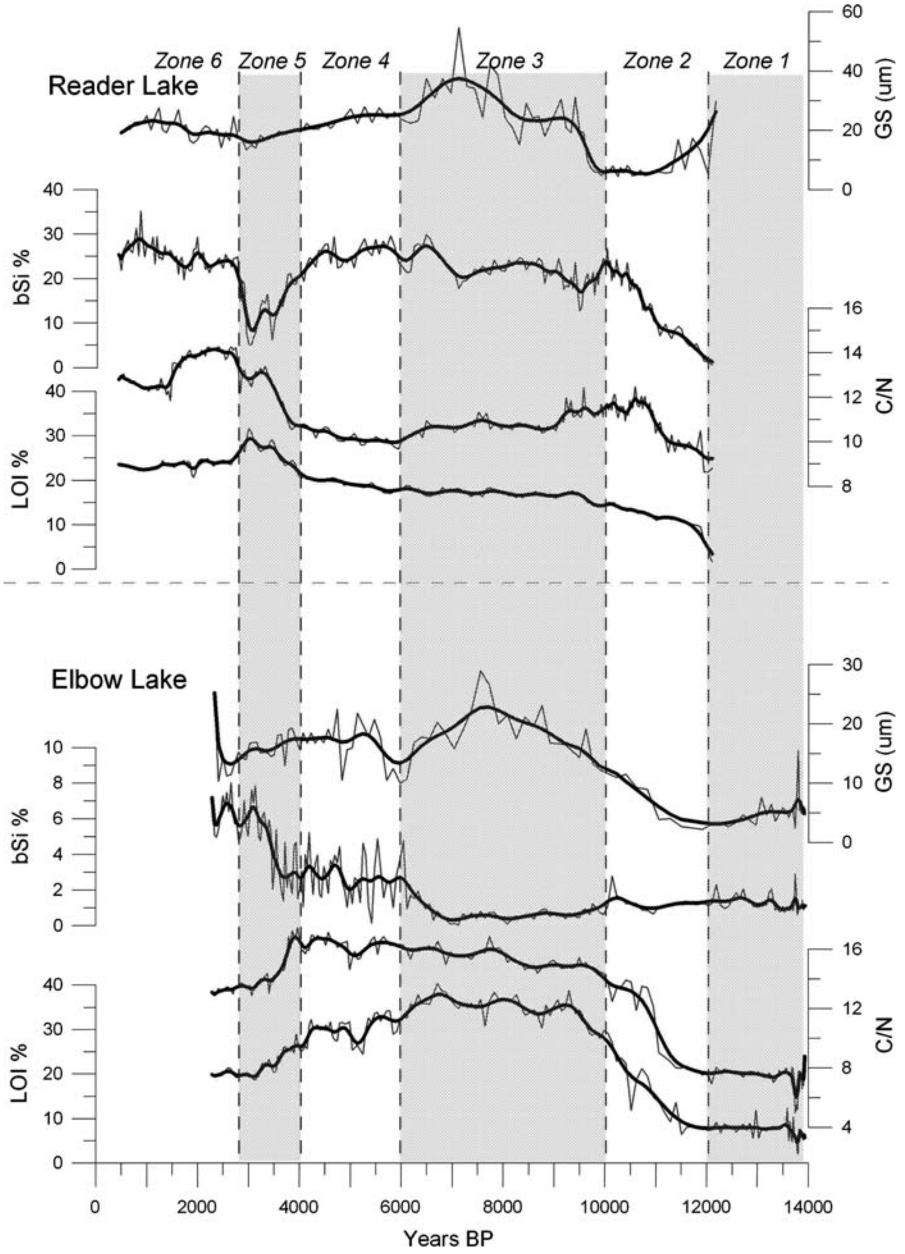
Radiocarbon dating

Radiocarbon results from the two cores are primarily in stratigraphic order (Fig. 2 and Table 2). The deepest age from Reader Lake is 12.2 ka BP, while the oldest date from Elbow Lake yields nearly 14 ka BP. Core top ages are approximations because they were determined through extrapolation. Nonetheless, the estimates (0.5 ka BP in Reader Lake, 2.3 ka BP in Elbow Lake) are reasonable considering that loose material from immediately below the sediment–water interface was not successfully recovered by the percussion corer. In the Reader Lake core, a pollen concentrate and a conifer needle from nearly the same depth (219 and 220.5 cm, respectively) returned overlapping ages (Table 2). Deeper in this core (239 cm) a pollen concentrate and a sample of *Daphnia* ephippia also returned similar ages. This convergence suggests that (1) the pollen concentrates can yield reliable radiocarbon age estimations, and (2) there is no appreciable hardwater effect that would complicate dating of aquatic organisms, which is consistent with the lack of carbonate bedrock in the watershed surrounding these lakes. The pollen concentrate from a depth of 153.5 cm in the Elbow Lake core, however, did not return an age that matched the *Daphnia* ephippia from the same depth (Table 2). Given the consistency of *Daphnia* ages from above and below this depth, this pollen based age determination was ignored in the depth-age model. Similarly, the deepest pollen based age from the Reader Lake core is inconsistent with the other dates so it too was ignored.

Time-series analyses

Figure 3 presents the time series of the four proxies investigated in the Reader Lake and Elbow Lake

Fig. 3 Time series of loss-on-ignition (LOI), carbon/nitrogen (C/N), biogenic silica content (bSi), and mean grain size (GS) data for the Reader Lake and Elbow Lake cores. LOI, C/N, and bSi were determined at 1 cm resolution, and GS was determined at 2 cm resolution. Zones identify time periods in which the majority of proxies have consistent trends. Zone boundaries were identified visually as times when the majority of proxies shift, and highlighting is intended to increase clarity. Joint consideration of all eight time series supports an integrated paleoclimate interpretation for this region. Details of how the proxies behave relative to one another at specific times reveals the importance of hydrogeomorphic setting in filtering the paleoclimate signals recorded in lake sediment



cores. The overall LOI pattern in Reader Lake is a steady rise upon which a short lived (about 1,000 year) increase to higher values (>30%) is superimposed. Values of C/N are at a minimum (<9) ca. 12 ka BP, rise to 10–12 between 11 and 9 ka BP, and then descend into a long period of low values extending until 4 ka BP. Values of C/N rise abruptly after 4 ka BP to a broad peak featuring the highest values in the time series (>14). This peak ends equally abruptly at 1.5 ka BP, when values drop again, but not to levels seen before the rise. The lowest values of bSi are found at the bottom of the core (<5%), but begin rising immediately to a sustained period from around 10 to 4 ka BP when values are consistently between 20 and 25%. This period ends with a precipitous drop to values <10% between 3.5 and 3.0 ka BP. After 3 ka BP, values rapidly recover and vary around 25% for the remainder of the record. Mean GS values in Reader Lake are very coarse (>30 μm) in the basal sediment and drop abruptly to values <10 μm in the silty clay. Between 10 and 6 ka BP values rise to a broad peak averaging about 25 μm, before falling until 4 ka BP. From 4 ka BP to the top of the record, GS is steady around 20 μm.

The time series determined for Elbow Lake generally exhibit shifts similar in phasing, but opposite in direction from those noted in the Reader Lake record. LOI remains low (5%) until about 11.5 ka BP, then rises steadily to a peak that persists from 10 to 6 ka BP. Values of C/N exhibit a nearly identical trend. Biogenic silica content is extremely low until about 6 ka BP when it abruptly rises and proceeds to vary around a mean of 3% until 3.5 ka BP. From 3.5 to 3.0 ka BP, values rise again to >6% and remain there until the end of the record. Mean GS is low (<10 μm) until 11.5 ka BP, then rises to a broad peak from 10 to 6 ka BP. Holocene minimum values are reached ca. 6 ka BP, after which GS rebounds somewhat before decreasing gradually until the end of the record.

Table 3 presents summary statistics for the four variables. Mean and median values are generally similar because most proxy measurements have quasi-normal distributions. The exception is bSi which is negatively skewed in Reader Lake, and positively skewed in Elbow Lake. Overall mean and maximum values of LOI and C/N are higher in Elbow Lake, yet this core also features the lowest C/N values found in both cores (ca. 5). Biogenic silica is quite different between the two records: values in Reader Lake range from 1 to over 35%, while values in Elbow Lake never rise above 8%. The sediment from Reader Lake is coarser (18.5 vs. 13.1 μm). C/N is the least variable proxy in both cores, however, its coefficient of variation is nearly three times greater in Elbow Lake (29.1 vs. 11.3). Grain size is the most variable proxy in the Reader Lake core, while bSi is the most variable in Elbow Lake. Overall, the Elbow Lake record is more variable with an average c.v. of 54.5 compared to 30.2.

Table 3 Summary statistics for the proxies measured in the Reader Lake and Elbow Lake cores

	LOI (%)	C/N	bSi (%)	GS (μm)
Reader lake				
Mean	18.6	11.6	20.5	18.5
Median	17.7	11.4	22.0	19.7
SD	5.1	1.3	6.4	9.4
c.v	27.5	11.3	31.1	51.0
Skewness	0.0	0.4	−1.0	0.5
Range	29.9	5.6	34.5	50.2
Minimum	1.7	8.6	0.7	4.4
Maximum	31.6	14.3	35.2	54.7
Elbow lake				
Mean	21.8	12.7	2.2	13.1
Median	22.8	14.0	1.3	14.6
SD	11.1	3.7	2.0	6.5
c.v	51.2	29.1	88.0	49.7
Skewness	−0.2	−0.6	1.3	−0.1
Range	38.1	12.5	7.9	26.8
Minimum	2.2	5.0	0.1	2.2
Maximum	40.3	17.5	8.0	29.0

Discussion

Joint consideration of the time series from both lakes supports development of an integrated paleoclimate record for this region. As noted above, most major shifts affecting more than one of the proxies are synchronous between the lakes even if the directions are contradictory. These shifts are used, therefore, to visually subdivide the time series into six zones in which most of the proxies exhibit distinct trends or values (Fig. 3). Paleoclimate interpretations are made for these zones given what is known about controls on the proxies and the similarities and differences between the physical settings of the two lakes.

Zone 1: 14.0–12.0 ka BP

The coarse sandy gravel at the base of the Reader Lake core is identical to glacial till revealed in natural exposures in the vicinity of these lakes. This similarity, combined with the razor-sharp contact between this basal member and the overlying silty clay, indicates that the Reader Lake core penetrated through the lacustrine section and into glacial sediment. The ages of the pollen concentrate and the *Daphnia* ephippia from this contact (239 cm) are 12.2 and 11.8 ka BP, respectively. Thus, we conclude that Reader Lake formed ca. 12 ka BP. In contrast, *Daphnia* ephippia isolated from the base of the Elbow Lake core returned an age of 13.9 ka BP, and because non-lacustrine material was not encountered at the bottom of this core, the true age of the lake could be even older (Fig. 2). This offset, therefore, demonstrates that Elbow Lake existed for at least 2,000 years before Reader Lake formed. This discrepancy can be explained by considering the geomorphic origin of the lake basins. Elbow Lake was excavated (at least locally) into bedrock by glacial erosion, as demonstrated by striated ledges near the junction of the two sub-basins. These basins would have collected water as soon as the area was deglaciated. Similar ledges are not present around Reader Lake, which is instead surrounded by hummocky glacial deposits. Reader Lake, therefore, appears to be a kettle formed through the melt-out of a buried glacial ice block, and the offset in the basal ages might reflect the time required for the ice to melt. Persistence of buried ice until ca. 12 ka BP could have been aided by cold conditions during the Younger Dryas stade (12.9–11.7 ka BP). Values of the measured proxies in Elbow Lake during this interval (Fig. 3) are consistent with a cold environment in which low water temperatures and prolonged ice cover inhibited primary productivity, resulting in low LOI (Shuman 2003) and bSi (Prokopenko et al. 2001). Dry conditions limited the in washing of terrestrial organic matter, resulting in low C/N (Ji et al. 2005), and the in washing of clastic debris, resulting in low GS. The three graded silt–clay couplets noted in the visual stratigraphy (Fig. 2) represent isolated exceptions to these conditions when the energy of sedimentation temporarily increased and large volumes of clastic sediment washed into the lake. In the thickest of these intervals, spanning 198–193 cm (ca. 13.8 ka BP), the lower silt layer has GS values twice those common to Zone 1, while values in the capping clay layer drop to 2.4 μm, near the lowest measured in the entire record.

Zone 2: 12.0–10.0 ka BP

Organic sedimentation began in both lakes during the period from 12.0 to 10.0 ka BP (Fig. 3). LOI in Reader Lake rises rapidly from less than 2 to 10% between 12.0 and 11.7 ka BP. After 11.7 ka BP, LOI continues to rise, but at a slower rate, reaching 14% by 10.0 ka BP. Values of LOI in Elbow Lake, which are steady around 10% in Zone 1, begin to rise at 11.4 ka BP and climb dramatically to 30% by 10.0 ka BP. In both records, the prolonged LOI rise starts at values of 10%, suggesting that this was a baseline condition common to both lakes at the onset of the Holocene. Similar rises in LOI were noted in other Uinta Mountain lakes by Munroe (2007). Elsewhere in the region, Fall et al. (1995) document an abrupt rise in LOI from 2 to greater than 20% near the bottom of a core from Rapid Lake, 250 km north of the Uinta Mountains. The onset of this rise is dated to ca. 13.2 ka BP (11,300 ^{14}C years BP), which is earlier than the increase documented in Reader Lake and Elbow Lake, however, there is concern that the bulk dates on gyttja supporting the depth-age model for this lake might be too old (Fall et al. 1995).

The rise in LOI spans a fundamental shift in sediment type from relatively inorganic silty clay to gyttja. Visually, this transition occurs in Reader Lake at 10.8 ka BP (215 cm) where interbeds of darker-brown relatively organic rich sediment begin to interrupt the redder, inorganic silty clay (Fig. 2). In Elbow Lake this transition occurs at 10.4 ka BP (143 cm) where the reddish silty clay alternates with the very dark gray silty gyttja (Fig. 2). In both lakes, the first darker colored, organic rich layers appear abruptly; given mean sedimentation rates of 0.20 mm/year in these cores, and no evidence of bioturbation at these contacts, the first appearance of darker layers may represent a change that occurred in less than a decade. Moreover, the inorganic silty clay layers interbedded with the organic rich sediment above this transition are not graded and there is no visible blurring of the two sediment types across layer boundaries. Thus the lakes seem to have alternated sharply between more- and- less productive states over a period of centuries. Overall, the evidence from Zone 2 indicates that the development of an aquatic biota abundant enough to impact the organic content of the sediment could occur quickly, but that the permanent establishment of this ecosystem required multiple events. A corollary to this interpretation is that the climate through this transition did not shift smoothly into a new, more stable mode, but rather oscillated in a way that frequently reset the aquatic ecosystem (Taylor et al. 1993).

Consideration of the other proxies adds additional details to the paleoclimate interpretation of Zone 2 (Fig. 3). Values of bSi begin to rise at 11.7 ka BP in Reader Lake, consistent with a transition to conditions more suitable for an abundant diatom population (i.e., warmer water and/or a longer ice free season, Blass et al. 2007). In Elbow Lake, however, the rise in LOI is not matched by a rise in bSi; instead, bSi values remain extremely low (less than 2%). At the same time in Zone 2, C/N values in Reader Lake are low (10–15), indicating that the organic matter accumulating in the lake was primarily of aquatic origin, and mean GS is falling to minimum values for the record. In contrast, most of the organic matter accumulating in Elbow Lake in Zone 2 was derived from terrestrial sources (C/N values in excess of 15), and GS was coarsening. This combination of proxies indicates that, while aquatic productivity was increasing in Reader Lake during the earliest Holocene, the amount of terrestrial organic and clastic material entering the lake was limited by the lack of an inflowing stream. In Elbow Lake, on the other hand, aquatic productivity remained minimal through Zone 2 and most of the increase in LOI was driven by increasing amounts of terrestrial organic matter entering the lake. Much of this material was likely delivered by the stream draining the wet meadow to the northwest of the lake. The corresponding increase in GS suggests that this stream was becoming increasingly competent as the post-glacial drainage system became better integrated. Increased turbidity in the water may have played a role in inhibiting the diatom population (Bradbury et al. 1994).

Zone 2 also witnessed the arrival of trees in the watersheds surrounding these lakes. In the Reader Lake core, the first conifer needle appeared in the sediment ca. 10.9 ka BP (221 cm). In Elbow Lake, the first needles appeared somewhat later, ca. 10.4 ka BP (143 cm). For comparison, 250 km east of the Whiterocks Basin, Feiler et al. (1997) document conifer needles in a core from a slightly lower elevation (3,165 m) by 10.7 ka BP (9,500 ^{14}C years). In the Wind River Range, Fall et al. (1995) conclude that a *Picea-Abies* forest was established around Rapid Lake (3,134 m) 12.7 ka BP (10,600 ^{14}C years), although the bulk ages from this core are thought to be too old (see above).

In Reader Lake and Elbow Lake, the arrival of trees overlapped with the visual transition to organic rich sedimentation, and occurred approximately 1,000 years after the onset of steadily rising LOI values. This offset indicates that the arrival of aquatic primary producers changed the organic content of the lake sediment, but that the lakes remained surrounded by a treeless tundra landscape for the next 1,000 years. Because these lakes are both less than 100 m below modern treeline, this evidence also reveals that treeline was near modern values by 10 ka BP. Similar conclusions were reached for the Wind River Range by Fall et al. (1995).

Zone 3: 10.0–6.0 ka BP

Many of the proxies reach extreme values in Zone 3 (Fig. 3). In Elbow Lake, LOI, C/N, and GS reach sustained highs, and bSi values fall to near their detection limit. The LOI values of 40% are higher than those reported for any other lakes in the Uinta Mountains (Munroe 2007; Munroe unpublished), even those at much lower elevations. The high C/N values indicate that large amounts of terrestrial organic material were being deposited in Elbow Lake, and the high GS values suggest that this material was being delivered by an enhanced fluvial system. The nearly nonexistent bSi content is consistent with a turbid environment. Together the proxies indicate that the period from 10.0 to 6.0 ka BP featured heightened precipitation volume over the Elbow Lake watershed (Noren et al. 2002; Brown et al. 2000). Because this watershed is steeper and higher (Table 1) and (at least today) less suitable for extensive forest cover, an increase in precipitation volume would greatly increase runoff into the lake (Dunn and Mackay 1995).

An increase in precipitation could also explain the shifts observed during Zone 3 in the proxies from

Reader Lake. Many of these proxies, however, change at different rates and in opposite directions because of the contrasting hydrogeomoprhic setting of the two lakes. Values of LOI and bSi continue to rise slowly through Zone 3, while values of C/N slowly fall. Because Reader Lake lacks an inflowing stream (Fig. 1), has a relatively small watershed/lake area ratio, a lower watershed elevation and lower watershed slopes (Table 1), and less exposed rock, increased precipitation would not have resulted in the delivery of large amounts of terrestrial organic material or clastic debris to the lake. LOI values continued to rise steadily, therefore, reflecting continued development of the aquatic ecosystem while values of C/N slowly fell as the increased deposition of aquatic organic matter outpaced the limited input of terrestrial material. Values of bSi stayed high as the diatom population thrived in the clear, shallow water.

Values of GS also rise in Reader Lake during Zone 3, but because the high bSi values argue against excessive turbidity and the low C/N values indicate minimal delivery of terrestrial organic matter, a different mechanism must have been responsible for delivering coarser clastic material to the coring site. One possibility is that these grains were transported from the littoral zone of the lake by enhanced waves and currents driven by higher wind speeds. The coarsest layers in Zone 3 have mean grain sizes (some greater than 40 μm) that are similar to those of the basal till unit, which is equivalent to the sediment exposed along the shoreline. Mean GS from both lakes also becomes more variable during Zone 3 (Fig. 3), indicating that high-energy precipitation events were more common (Noren et al. 2002). Intense storms would deliver larger clastic material to the coring site in Elbow Lake through flooding on the inlet stream, while in Reader Lake storms would drive increased shoreline erosion and wave-driven redeposition of littoral sediment.

The time period of Zone 3 corresponds with changes in solar insolation that have been invoked as a driver of enhanced summer monsoon circulation in the early Holocene (Berger 1978; Thompson et al. 1993). Reader Lake and Elbow Lake are located today in a monsoon-dominated climate (Munroe 2003), and studies have suggested that this precipitation regime was more pronounced during the early Holocene (Thompson et al. 1993; Whitlock and Bartlein 1993). Indeed, recent work reveals wet conditions and increased flow in the Bear River, which drains the northwestern Uintas, during the period from 9.2 to 7.2 ka BP (Moser and Kimball 2009). Shuman et al. (2009) proposed that water levels in many Rocky Mountain lakes were low in the middle Holocene after 8 ka BP, which overlaps with the period of increased precipitation inferred for Zone 3; however, the combined records from Reader Lake and Elbow Lake are consistent with the general consensus that precipitation increased over this region in the early Holocene.

Zone 4: 6.0–4.0 ka BP

The period from 6.0 to 4.0 ka BP represent a transition out of the wet climate that characterized the early Holocene (Fig. 3). In Reader Lake, LOI continues the steady rise that began ca. 11.7 ka BP, C/N remains low, and bSi remains high, indicating the persistence of a productive lacustrine environment. Mean GS falls dramatically from the values reached in Zone 3, indicating that redeposition of littoral sediment was greatly reduced. Similarly, in Elbow Lake, LOI and GS decrease, suggesting a lessening of the fluvial inflow to the lake. Values of bSi increase notably at 6 ka BP, demonstrating the development of a diatom population for the first time in the Elbow Lake record, possibly in response to decreasing turbidity (Bradbury et al. 1994). Overall, the proxies appear to record a slow drying trend in this region during the middle Holocene. The C/N time series in Elbow Lake is the one proxy that does not fit with this interpretation. For unknown reasons, C/N remains high through Zone 4, suggesting that terrestrial material continued to enter Elbow Lake in quantities sufficient to offset the blossoming diatom population.

Zone 5: 4.0–2.7 ka BP

The period from 4.0 to 2.7 ka BP marks the time when the Reader Lake and Elbow Lake records differ the most (Fig. 3). In Reader Lake, values of LOI and C/N increase, while bSi and GS decrease. For LOI, this is the first departure from the steady rising trend in nearly 8,000 years. Values of C/N increase to record levels, bSi drops by an order of magnitude, and GS reaches low values not seen since the early Holocene. In contrast, in Elbow Lake LOI and C/N both drop following prolonged intervals of high values, and biogenic silica rises abruptly to unprecedented levels. The only consistency is that GS decreases in both records; the directions of all other proxy shifts are inverted.

Considered together, these shifts are consistent with unprecedented drought. This dry period was apparently profound enough to turn Reader Lake into a wet meadow, increasing LOI as the sediment became peaty (as noted in the visual stratigraphy), increasing C/N as the organic matter became increasingly terrestrial, decreasing bSi as the diatom population dropped (Chu et al. 2002), and decreasing GS as redistribution of littoral sediment ceased. In Elbow Lake, LOI is mainly controlled by fluvial input of terrestrial organic matter (as revealed by the C/N values), so a drought that reduced the river flow to the lake would decrease LOI and C/N, as well as GS. Values of bSi step upward again at the same time that C/N abruptly drops (ca. 3.5 ka BP) because the water was finally clear enough to allow abundant diatom growth.

Other studies have reported climatic perturbations during this time period. Booth et al. (2005) summarize evidence for a sustained continental-scale drought in central North America between 4.4 and 4.0 ka BP. Datapoints for this interpretation range from lake and bog studies in the upper Midwest, to evidence for sand dune activation 500 km east of the Uinta Mountains in eastern Wyoming and Colorado (Forman et al. 1995; Stokes and Gaylord 1993). In the northern Rocky Mountains, Stone and Fritz (2006) documented a pronounced shift in diatom-inferred hydroclimate between 4.5 and 3.5 ka BP. At the broadest scale, Mayewski et al. (2004) identified periods of rapid climate change in globally distributed Holocene climate records, one of which extended from 4.2 to 3.8 ka BP and another from 3.5 to 2.5 ka BP. Both of these overlap with Zone 5 in the combined Reader Lake and Elbow Lake records. While the drivers responsible for climatic shifts at this time have not been identified, the overall pattern suggests a profound, transient reorganization of the climate system ca. 4 ka BP.

Zone 6: 2.7 ka BP—core tops

Interpretation of Zone 6 is hindered by the relatively old core top age for Elbow Lake (2.3 ka BP), yet it is still apparent that after 2.7 ka BP most of the proxies in Reader Lake return to values that prevailed before Zone 5, while most of those in Elbow Lake remain shifted. In Reader Lake, LOI, bSi, and GS all suggest that the system recovered as the drought ended. The one anomaly is C/N, which remains high until 1.5 ka BP. As with the C/N trend in Zone 4 in Elbow Lake, it is not clear what mechanism is responsible for maintaining these elevated values. One possibility is that shoreline transgression associated with a rising water level continually eroded and redeposited terrestrial organic matter that had accumulated around Reader Lake during the Zone 5 low stand, keeping C/N values high despite the lack of an inflowing stream.

In the Elbow Lake record, values of LOI, C/N, and GS remain low in Zone 6, implying that terrestrial in washing did not return to pre-drought levels. An exception is the uppermost GS sample, but because it is from the very top of the recovered section, it may have been contaminated by coarser material during core retrieval. Biogenic silica stays near record highs, indicating that the well established diatom population remained stable in consistently clear water. The divergence between the records from the two lakes in Zone 6 may indicate that summer precipitation remained low while winter precipitation increased. Low summer precipitation would have limited the amount of terrestrial material entering Elbow Lake during storm events, thus keeping LOI, C/N, and GS low, while allowing bSi to remain high. Increased winter precipitation would have allowed the groundwater table to rise again, raising water levels to pre-drought levels in the shallow Reader Lake kettle, but without impacting the record of the deeper Elbow Lake significantly.

Conclusions

Paleolimnological investigation of Reader Lake and Elbow Lake in the Uinta Mountains of Utah yields an integrated paleoclimate history for this region. A cold climate in the latest Pleistocene kept biologic productivity to a minimum in Elbow Lake between 14 and 11.5 ka BP. Reader Lake formed as a kettle following melt-out of a buried ice block at the end of the Younger Dryas ca. 12 ka BP. Both lakes became biologically productive between 11 and 10 ka BP. The first appearance of organic rich sediment was abrupt, but the establishment of a permanent productive aquatic ecosystem occurred through a transition interval in which the lakes oscillated between more- and less- productive states. Conifers reached the elevation of the lakes, which are less than 100 m below modern treeline, during this transition period. In the early Holocene, a prolonged interval of heightened precipitation volume, likely driven by insolation enhancement of the summer monsoon, increased fluvial inputs to Elbow Lake, while an enhanced wind regime increased the redistribution of littoral sediment in Reader Lake. Between 6 and 4 ka BP, the enhanced precipitation regime decreased, and sustained drought occurred from 4 to 2.7 ka BP. During this time, Reader Lake converted to a shallow wetland, and fluvial input to Elbow Lake decreased markedly, allowing an abundant diatom community to become established in clear water for the first time. After 2.7 ka BP, proxies in Reader Lake returned to deeper water conditions, yet proxies in Elbow Lake remained in a state suggestive of minimal fluvial inflow, perhaps reflecting a shift in the seasonality of precipitation. Collectively, this multiproxy-based paleoclimate reconstruction corresponds well with other records from the surrounding region.

A strength of this interpretation is the combination of sedimentary records from two neighboring lakes in strongly contrasting hydrogeomorphic settings. Because of their close proximity, Reader Lake and Elbow Lake must have been subjected to the same climatic forcing during the Holocene. However, comparison of their sedimentary records reveals that throughout much of the post-glacial period, proxies in the two records shift at the same time but in opposite directions. Shifts toward greater precipitation volume are registered as rising LOI, C/N, and GS in Elbow Lake as fluvial inputs increased. Reader Lake, on the other hand, is relatively insensitive to increased precipitation volume, given its lack of an inflowing stream, its location near the highest point reached by the water table aquifer, and the geometry of its broad outlet that precludes significant increases in water level. Decreases in precipitation are also recorded differently. In Reader Lake, decreased precipitation would have converted the shallow lake to a wetland, increasing LOI and C/N, and decreasing bSi and GS. In contrast, Elbow Lake values of LOI, C/N, and GS would have dropped during a drought because of the great reduction in fluvial input. Biogenic silica would increase because of the improvement of water clarity.

An important conclusion from this work is the realization that considering either record in isolation would lead to more equivocal, if not erroneous, interpretations. When considered together, however, the differing sensitivities of the lakes yield increased interpretative power. This example underscores the importance of considering hydrogeomorphic setting when evaluating the suitability of a specific lake for a paleolimnological study.

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