INVESTIGATING THE INFLUENCE OF HYDROGEOMORPHIC SETTING ON THE RESPONSE OF LAKE SEDIMENTATION TO CLIMATIC CHANGES

Lee B. Corbett[1]
Jeffrey S. Munroe
Department of Geology
Middlebury College
Middlebury, VT 05753

Keywords: Utah, Uinta Mountains, lake sediment, hydrogeomorphology, drought, precipitation

[1] Current Address: Department of Geology, University of Vermont, Burlington VT, 05405, 802-380-2344, abcorbet@uvm.edu

Abstract

Reader Lake and Elbow Lake, two high altitude lakes in the Uinta Mountains of Utah, are located about 2 km apart, at similar elevations, and within identical vegetation communities. Despite their proximity, however, climate reconstructions from sediment cores suggest that the lakes have responded to post-glacial climate changes in notably different ways. The goal of this study is to clarify how each lake has responded to past climate changes and to understand why the two lakes have behaved so differently over time. Loss on ignition (LOI), biogenic silica (BSi), carbon to nitrogen ratios (C/N), and grain size distribution were analyzed at 1-cm intervals throughout both cores to construct continuous records spanning ca. 14 ka BP to ca. 2 ka BP. The Reader Lake record features high variability in LOI, BSi, and mean grain size, and shows an anomalous excursion centered on 4.2 ka BP. The Elbow Lake record features high variability in LOI, C/N, and mean grain size, with sustained high values of these three proxies between 10 and 4 ka. Given the proximity of the two lakes, it can be assumed that climatic forcing was the same for both lakes over time. Therefore, the dissimilarity of the two sediment records likely reflects differences in watershed hydrogeomorphology and lake bathymetry. Reader Lake, which is shallow and lacks an inflowing stream, is likely sensitive to drought. Elbow Lake, which is deep and has a large through flow, may be sensitive to changes in terrestrial inwash. Past changes in the amount or intensity of precipitation over this watershed may, therefore, have impacted the two lakes in different ways, underscoring the need to consider hydrogeomorphic setting when evaluating the suitability of a specific lake for a paleolimnological study.

Introduction

Multiproxy analysis of lacustrine sediment cores is a powerful method for creating detailed paleoclimate reconstructions. Paleoenvironmental information can be extracted from numerous proxies including diatom and chironomid population distributions (e.g. Stone and Fritz, 2006; Porinchu et al., 2003), biogenic silica abundance (e.g. Blass et al., 2007), organic matter content (e.g. Munroe, 2007), pollen grains (e.g. Mensing et al., 2004), charcoal abundance (e.g. Brunelle and Anderson, 2003), grain size distribution (e.g. Noren et al., 2002), and organic and inorganic chemical characteristics (e.g. Dean et al., 2002). Variation in these proxies is often interpreted as a sign of paleoclimatic change. However, interpretations of lake sediment records must also consider the extent to which the physical setting of a lake basin might impact the sensitivity of different proxies to climatic change.

Recent work has considered how the physical setting of a lake basin may affect the response of lacustrine loss-on-ignition (LOI) records to climatic change (Munroe, 2007). One of the greatest factors is hydrologic setting, with lakes connected to high-volume inflows and outflows exhibiting steady LOI records over time, while hydrologically closed basins feature more variable LOI over time (Munroe, 2007). These results highlight the potential for erroneous paleoclimate interpretations if a single core is used to broadly represent an area without consideration of the way in which hydrogeomorphic setting might filter the paleoclimate signal.

To explore this question further, this study considered sediment cores retrieved from two small high-altitude lakes in the Uinta Mountains of northeastern Utah (Figure 1). Both lakes formed during the Latest Pleistocene deglaciation and are located in the same river basin and at similar elevations, are surrounded by the same vegetation community, and are less than 2 km apart. The lakes differ, however, in their hydrologic settings. Because of the proximity of the lakes, Holocene climate variations at each site should have been nearly identical. The goal of this study, therefore, is to explore how the differing watershed hydrogeomorphology and bathymetry of the two lakes has impacted the way that their sediments record past climatic change.

Study site

Geology and climate of the Uinta Mountains

The Uinta Mountains form the longest east-west trending range in the western United States, stretching approximately 200 km across northeastern Utah (Figure 1). The highest peaks in the range rise to elevations over 4 km and support extensive areas of alpine tundra. The core of the range consists of a series of Neoproterozoic sedimentary rocks (chiefly quartzite, shale, and sandstone) that accumulated in a marine deltaic system 850-750 Ma (Dehler and Sprinkel, 2005). During the Laramide orogeny (ca. 60 Ma BP), these rocks were uplifted and folded into an east-west oriented doubly plunging anticline, the axis of which roughly corresponds to the crest of the mountains (Paulsen and Marshak, 1999).

Although no glaciers exist in the Uinta Mountains today, the rugged topography and abundant glacial features in the range indicate that alpine glaciers were present during the Pleistocene. Munroe et al. (2006) conclude that the last deglaciation began by 16 ka BP, and Munroe (2002) suggests that the latest Pleistocene deglaciation was complete by 14-15 ka BP. Reconstruction of range-wide glacier equilibrium line altitudes indicates that summer temperatures during the last glacial maximum were 5.5 to 8˚C colder than present (Munroe and Mickelson, 2002), while modeling by Laabs et al. (2006) suggests that temperatures during the last glacial maximum were 6 to 7˚C colder and precipitation was between 1 and 2 times greater than present-day values.

Surface runoff from the Uinta Mountains feeds the Bear, Weber, and Provo Rivers and is an important source of water for Utah and the Great Basin. Of the 1.8 km^3 of surface runoff water produced in the Uinta Mountains each year (Jeppson et al., 1968; U.S. Forest Service, 1976), about 68% feeds the Green River, a major tributary to the Colorado River (Osteler, 1982). Stockton and Jacoby (1976) estimate that runoff from the Uinta Mountains makes up about 9% of the Colorado River's total supply.

Reader Lake and Elbow Lake

The two lakes targeted in this study are located less than 2 km apart in the Whiterocks Basin in the southeastern Uinta Mountains (Figure 2). Reader Lake, at an elevation of 3341 m, has a circular shape, reaches a depth of 4 m, and has gently sloping sides. There is currently an ephemeral outlet but no inflow. The lake's surface area is 4.8 ha and the watershed area is 54 ha. Elbow Lake, at an elevation of 3326 m, has a more complex shape, a maximum depth of almost 11 m, and steeply sloping sides. The lake has a prominent inflow through a wet meadow complex that has formed a large delta in the northwestern corner of the lake. The areas of the lake's surface and the watershed are 10 and 335 ha, respectively. Both lakes are located near cirque headwalls and are surrounded by a closed forest of *Picea engelmannii* (Engelmann spruce) and *Abies lasiocarpa* (subalpine fir).

Methods

Sample collection and age control

Cores were collected in July 2004 (Elbow Lake, 216 cm in length) and July 2005 (Reader Lake, 245 cm in length). Cores were taken from an anchored platform with a modified percussion corer and 3-inch diameter PVC pipe (Reasoner, 1993). In the field, cores were cut into sections roughly 60-80 cm in length, capped, and carried out on packhorses, then stored at 5˚C upon arrival at Middlebury College. Before sampling, cores were split lengthwise into two sections; one of these sections was wet sieved in 1-cm slices at 500 µm to separate terrestrial macrofossils suitable for radiocarbon dating while the other section was divided into four 3 cm^3 samples at 1-cm intervals.

Organic macrofossils were sent to the University of Arizona AMS Laboratory and the Woods Hole NOSAMS Facility for AMS radiocarbon dating. From Reader Lake six macrofossils were dated: an organic fragment from 32 cm, conifer needles from 106.5 and 150.5 cm, *Pinus* pollen concentrate from 219 cm, a needle from 220.5 cm, and *Daphnia* ephippia from 239 cm. Six macrofossils were also dated from the Elbow Lake core: *Daphnia* ephippia from

30.5 cm, needles from 96.5, 127.5, and 142.5 cm, and *Daphnia* ephippia from 153.5 and 216.5 cm. Ages were calibrated into calendar years using the online version of Calib 5.0.

Sample analysis

Four environmental proxies were used for the interpretation of lake sediment cores in this study: loss-on-ignition (LOI), carbon to nitrogen (C/N) ratios, biogenic silica (BSi), and grain size distribution. As described by Dean (1974), LOI gives 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, where a higher C/N is characteristic of a more terrestrial source (e.g. Sampei and Matsumoto, 2001). BSi analysis quantifies the proportion of organically derived SiO_2 produced from diatoms and serves as a proxy for primary productivity within the lake (e.g. DeMaster, 1981; Peinerud et al., 2001). Grain size distribution provides information about terrestrially derived clastic material and is useful for identifying changes in the energy of inflowing water and turbidity within the lake (e.g. Noren et al., 2002).

Samples taken at 1-cm intervals throughout the cores were analyzed for the four properties described above. LOI analysis was performed on a Leco Corp TGA-701 thermogravimetric analyzer using a protocol developed at Middlebury College. Samples were first heated to 105˚C for 4 hours under a 100% N_2 atmosphere to determine water content, then to 550˚C for 3 hours under ambient atmosphere to determine organic matter content, and finally to 1000˚C under ambient atmosphere to determine carbonate content. C/N analysis was performed on a CE Instruments NC 2500 elemental analyzer (EA) using Eager 200 data handling software. The precision of the analyzer was approximately 1% of the quantity measured for %C and 0.5% for %N. Samples were analyzed for BSi with a method adapted from Mucciarone (2003) that involved hourly extractions during a 5-hour leach in 0.1M sodium hydroxide to differentiate between mineral and biologic Si. 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. Grain size samples were prepared with 35% hydrogen peroxide and 0.1M sodium hydroxide to dissolve organic matter and diatoms, and were then analyzed in a Horiba Laser Spectrometer LA-920.

Results

Reader Lake

Overall, the Reader Lake record features high variability in LOI, BSi, and mean grain size, but low variability in C/N (Figure 3). Sedimentation began in Reader Lake at 12.4 ka BP and was characterized by low LOI, C/N, and BSi, and fine mean grain size (roughly 1%, 10, 1%, and 5 µm, respectively). From that point, LOI and BSi increase rapidly until 9 ka BP, reaching 15% and 25% respectively. Between ~9 and 6 ka BP, LOI, BSi, and mean grain size are highly variable, although C/N remains relatively constant at its original value of about 10. From ~6 to 4.4 ka BP, LOI increases and BSi decreases rapidly while mean grain size becomes finer. Between 4.4 and 3.9 ka BP the sedimentary regime is unlike any other interval in the record and is characterized by extremely high LOI (over 30%) and C/N (over 13), low BSi (5%), and fine mean grain size (below 10 µm). After 3.9 ka BP, LOI decreases and BSi increases, both to between 20 and 25%, realigning with their pre-4.4 ka BP values. C/N remains elevated at around 12 to 13 while mean grain size remains fine and highly variable.

Elbow Lake

Overall, the Elbow Lake core shows high variability in LOI, C/N, and mean grain size, but low variability in BSi (Figure 4). Sedimentation in Elbow Lake began at 14.1 ka BP and is characterized by low LOI, C/N, and BSi, and fine mean grain size (roughly 5%, 6, 1%, and 6 µm, respectively). This pattern persists for almost 4 ka BP until all proxies (excluding BSi) increase sharply. Beginning at 9 ka BP and lasting until 4 ka BP, LOI remains between 25 and 40%, C/N reaches about 15, mean grain size is generally coarse (averaging roughly 16 µm), and all three are highly variable. After 3.9 ka BP, LOI decreases to less than 20%, C/N decreases to about 13, BSi increases to around 5%, and grain size maintains a similar mean but becomes less variable.

Discussion

Comparison between records

A comparison of climate reconstructions from Reader Lake and Elbow Lake shows notable differences. Reader Lake features relatively stable C/N and high variability in LOI, BSi, and mean grain size. Conversely, Elbow Lake features stable BSi and high variability in LOI, C/N, and grain size. The Reader Lake record is a rapidly changing system that seldom reaches equilibrium, while the Elbow Lake record appears to fall into three distinct phases (roughly 14 – 10 ka BP, 9 – 4 ka BP, and 4 – 2 ka BP) that are each relatively stable. The Reader Lake record shows a large perturbation centered on 4.2 ka BP, while the same time in the Elbow Lake record is characterized only by a shift between two phases.

The role of geomorphology

Because of their close proximity and similar settings, it is reasonable to assume that Reader Lake and Elbow Lake were subjected to the same climate forcings during the Holocene. The contrasts in their sedimentary records, therefore, likely reflect differences in the way the lakes record changes due to differences in their physical settings. We infer that Reader Lake, which lacks an inflowing stream, would be less influenced by terrestrial inwash than Elbow Lake, which has a large inflow and deltaic system. During times of heightened precipitation, Reader Lake would be impacted only by enhanced overland flow, but Elbow Lake would experience increased volumes of both overland flow and channelized drainage. Conversely, Reader Lake should be more sensitive to drought than Elbow Lake because of its relative shallowness and gently sloping bathymetry. Given these characteristics, even a small decrease in water volume could cause a significant reduction in Reader Lake's surface area and depth, while simultaneously increasing the area of fringing wetlands. Because the two sediment records differ greatly, we argue that the hydrogeomorphic setting of each lake dictates how sedimentation responded to Holocene changes in precipitation volume and intensity.

Paleoclimate and geomorphology

Both sediment records begin with low LOI and BSi, suggesting minimal organic productivity both in and around the lakes. Since the alpine glaciers did not disappear from the Uintas until 14-15 ka BP (Munroe, 2002), this sedimentary regime likely reflects a cold post-glacial climate with minimal primary productivity in the watershed. Productivity (as measured by LOI and BSi) begins to increase in Reader Lake ~12.4 ka BP and in Elbow Lake ~10.5 ka BP. This time lag may be attributed to the greater water depth of Elbow Lake and the presence of a large inflow, both of which would have made conditions difficult for the establishment of primary producers. The magnitude of this lag may also be exaggerated by errors in the depth-age model, which is less well-constrained in these deep, organic-poor sediments. By about 9 ka BP, high LOI and BSi values in both cores indicate that the climate had moderated enough to allow diatoms and more complex organisms to start playing an important role in the lakes' sedimentation.

In both lakes, 9 ka BP also marks a transition in sediment characteristics. Both cores begin to show increased variability in LOI and mean grain size, suggesting that episodic storm events were transporting coarser material and more terrestrial matter into the lakes (e.g. Noren et al., 2002). This variability is visible in both records because both lakes would have been impacted by a climatic shift featuring more frequent intense precipitation events and episodes of overland flow. Only Elbow Lake, however, shows a prolonged plateau of heightened LOI and C/N in addition to this variability described above. This combination indicates that the background amount of terrestrial organic matter entering Elbow Lake increased in concert with the shift to more frequent storms, suggesting that the total volume of precipitation also increased. Both lakes may, therefore, have experienced an increase in precipitation volume and intensity ca. 9 ka BP. Due to differences in hydrogeomorphic setting, Reader Lake only recorded evidence for the increase in precipitation intensity, while Elbow Lake recorded a more complete picture of the changing precipitation regime.

The time interval when the Reader Lake and Elbow Lake records differ most is from 4.4 to 3.9 ka BP. In Reader Lake, this interval is characterized by unprecedented high levels of LOI and low levels of BSi, in addition to fining mean grain size and an increase in C/N. Taken together, the trend of these proxies suggests that the influx of terrestrial organics increased while both diatom abundance and the energy of terrestrial input decreased. This trend is consistent with prolonged drought during which overland flow waned, decreasing the transport of clastic material into the lake. Lake level would have dropped to reflect a new hydrologic balance, which would have converted the extensive shallow areas along the perimeter of the lake to wetlands. Increasing wetland fringe would have contributed to a pronounced increase in both LOI and C/N. Finally, the diatom population may have declined in response to the diminished area of open water.

In contrast, the proxies investigated in the record from Elbow Lake do not exhibit major changes during the interval between 4.4 and 3.9 ka BP. Instead this time period is marked only by a decrease in LOI and C/N, a gradual fining of mean grain size, and a slight increase in BSi, a trend which had begun at roughly 6 ka BP. The behavior of the proxies at this time suggests that precipitation volume and severity decreased, therefore transporting less terrestrially derived material into the lake and allowing diatoms to become established. Elbow Lake apparently did not experience a pronounced drying event like Reader Lake did, probably because the bathymetry of the lake made it less sensitive to decreases in water level.

Mid-Holocene drought

Other paleoclimate reconstructions from the western U.S. have identified a drought event centered on 4.2 ka BP. A review by Booth et al. (2005) suggests that dune reactivation, heightened forest fire frequency, low water table levels, and changes in forest composition were widespread in the central part of North America between 4.1 and 4.3 ka BP. Near the Uinta Mountains, dunes were reactivated in northeastern Colorado and central Wyoming at this time (Forman et al., 1995; Stokes and Gaylord, 1993), and diatom records from lake sediment in northwestern Montana indicate a profound change in hydrologic balance (Stone and Fritz, 2006). The causal mechanisms of this drought are not well understood. As described by Booth et al. (2005), this event may have been caused by external forcing (e.g. non-linear response to Milankovitch forcing, decreased solar radiation, or changes in volcanic forcing) or by internal variability in the ocean-atmosphere system.

Because surface runoff from the Uinta Mountains makes up 9% of the Colorado River's total supply (Stockton and Jacoby, 1976), understanding drought in this region is important for the cities and agricultural areas that rely on the Colorado River's water. This is especially relevant because the population of the southwestern United States is growing rapidly, and the supply of water is already having trouble keeping up with demand. Drysdale et al. (2006) suggest that a link exists between severe Holocene drought ca. 4.2 ka BP and the collapse of several ancient civilizations, highlighting the importance of understanding the frequency and severity of drought in populated areas.

Implications for future paleolimnological studies

If just the Reader Lake core had been collected from this drainage, the conclusions would be notably different than if just the Elbow Lake core had been collected. In the first case, the paleoclimatic interpretation might suggest that precipitation intensity was variable and that a pronounced drought occurred ca. 4.2 ka BP. In the second case, the paleoclimatic interpretation might indicate that precipitation volume was high throughout the middle of the Holocene, and would likely miss the 4.2 ka BP drought entirely. This work, therefore, suggests that the practice of using one core from one lake to represent a certain geographic region should be reevaluated.

This study demonstrates that hydrogeomorphic setting plays an important role in determining how lake sediment records changes in climate. Therefore, it may be helpful to retrieve cores from several different lakes and to use this information to piece together a more comprehensive history. Or, if only one lake can be cored, it may be helpful to carefully consider the hydrogeomorphic setting of each possible lake before selecting the final site. A lake with an inflow, for instance, may be best at showing changes in precipitation volume and would be ideal for investigators hoping to learn about monsoon strength. A closed basin, on the other hand, might be an ideal setting to learn about drought.

Conclusions

Sedimentalogical investigation of Reader Lake and Elbow Lake in the Uinta Mountains of Utah suggests that the region was characterized by cold, harsh climate in the Late Pleistocene, variable precipitation strength in the early and mid Holocene, severe drought ca. 4.2 ka BP, and relative stability in the late Holocene. Comparison between the paleoenvironmental records shows that the two lakes have notably different histories, despite their similar settings and close proximity. This discrepancy is likely caused by differences in watershed hydrogeomorphology and lake bathymetry, and indicates the importance of considering hydrogeomorphic setting when evaluating the suitability of a specific lake for a paleolimnological study.

Acknowledgements

Financial support for this project was provided by the National Science Foundation grant EAR 0345112 and the Middlebury College Senior Work Fellowship. Field and laboratory support was provided by the Ashley National Forest, M. Devito, N. Oprandy, B. Laabs, D. Munroe, A. Lini, C. Anderson, D. Berkman, B. Fisher, and C. Rodgers.

References

Blass, A, Bigler, C, Grosjean, M, and Sturm, M (2007) Decadal-scale autumn temperature reconstructions back to AD 1580 inferred from varved sediments of Lake Silvaplana (southeastern Swiss Alps). Quaternary Res 68: 184-195.

Booth, RK, Jackson, ST, Forman, SL, Kutzbach, JE, Bettis, EA, Kreig, J, and Wright, DK (2005) A severe centennial-scale drought in mid-continental North America 4200 years ago and apparent global linkages. The Holocene 15: 321-328.

Brunelle, A, and Anderson, RS (2003) Sedimentary charcoal as an indicator of late-Holocene drought in the Sierra Nevada, California, and its relevance to the future. The Holocene 13: 21-28.

Dean, WE (1974) Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J Sediment Petrol 44: 242-248.

Dean, WE, Forester, RM, and Bradbury, JP (2002) Early Holocene change in atmospheric circulation in the Northern Hemisphere Great Plains: an upstream view of the 8.2 ka cold event. Quaternary Sci Rev 21: 1763-1775.

Dehler, CM and Sprinkel, DA (2005) Revised stratigraphy and correlation of the Neoproterozoic Uinta Mountain Group, northeastern Utah. In: Dehler, CM, Pederson, JL, Sprinkel, DA, and Kowallis, BJ (eds.) Uinta Mountain Geology. Utah Geological Association Publication 33, Salt Lake City, pp17-30.

DeMaster, DJ (1981) The supply and accumulation of silica in the marine environment. Geochim Cosmochim Acta 45: 1715-1732.

Drysdale, R, Zanchetta, G, Hellstrom, J, Maas, R, Fallick, A, Picket, M, Cartwright, I, and Piccini, L (2006) Late Holocene drought responsible for the collapse of Old World civilizations is recorded in an Italian cave flowstone. Geology 34: 101-104.

Forman, SL, Oglesby, R, Markgraf, A, and Stafford, T (1995) Paleoclimatic significance of lae Quaternary eolian deposition on the Piedmont and High Plains, central United States. Global Planet Change 11: 35-55.

Jeppson, RW, Ashcroft, GL, Huber, AL, Skogerboe, GV, and Bagley, JM (1968) Hydrologic Atlas of Utah. Utah Water Research Laboratory, Utah State University, Logan, Utah. Publication No. PRWG 35-1.

Laabs, BJC, Mitchell, AP, and Mickelson, DM (2006) Climate during the last glacial maximum in the Wasatch and southern Uinta Mountains inferred from glacier modeling. Geomorphology 75: 300-317.

Mensing, SA, Benson, LV, Kashgarian, M, and Lund, S (2004) A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. Quaternary Res 62: 29-38.

Mucciarone, DA (2003) Stanford University Stable Isotope Laboratory Online Manual. Section 6A: Biogenic Silica. Available online at: http://pangea.stanford.edu/research/isotope/dam/pdf/Stanford_SIL_Online_manual.pdf.

Munroe, JS (2007) Exploring relationships between watershed properties and Holocene loss-on-ignition records in high-elevation lakes, southern Uinta Mountains, Utah, USA. Arct Antarct Alp Res 39: 556-565.

Munroe, JS (2002) Timing of postglacial cirque reoccupation in the northern Uinta Mountains, northeastern Utah, USA. Arct Antarct Alp Res 34: 38-48.

Munroe, JS, Laabs, BJC, Shakun, JD, Singer, BS, Mickelson, DM, Refsnider, KA, and Caffee, MW (2006) Latest Pleistocene advance of alpine glaciers in the southwestern Uinta Mountains, Utah, USA: Evidence for the influence of local moisture sources. Geology 34: 841-844.

Munroe, JS and Mickelson, DM (2002) Last glacial maximum equilibrium-line altitudes and paleoclimate, northern Uinta Mountains, Utah, USA. J Glaciol 48: 257-266.

Noren, AJ, Bierman, PR, Steig, EJ, Lini, A, and Southon, J (2002) Millennial-scale storminess variability in the northeastern United States during the Holocene epoch. Nature 419: 821-824.

Ostler, WK, Harper, KT, McKnight, KB, and Anderson, DC (1982) The effects of increasing snowpack on a subalpine meadow in the Uinta Mountains, Utah, U.S.A. Arctic Alpine Res 14: 203-214.

Paulsen, T and Marshak, S (1999) Origin of the Uinta recess, Sevier fold-thrust belt, Utah: influence of basin architecture on fold-thrust belt geometry. Tectonophysics 312: 203-216.

Peinerud, EK, Ingri, J, and Pontér, C (2001) Non-detrital Si concentrations as an estimate for diatom concentrations in lake sediments and suspended material. Chem Geol 177: 229-239.

Porinchu, DF, MacDonald, GM, Bloom, AM, and Moser, KA (2003) Late Pleistocene and early Holocene climate and limnological changes in the Sierra Nevada, California, USA, inferred from midges (Insecta: Diptera: Chironomidae). Palaeogeogr Palaeoecol 198: 403-422.

Reasoner, M (1993) Equipment and procedure improvements for a lightweight, inexpensive, percussion core sampling system. J Paleolimnol 8: 273-281.

Sampei, Y and Matsumoto, E (2001) C/N ratios in a sediment core from Nakaumi Lagoon, southwest Japan- usefulness as an organic source indicator. Geochem J 35: 189-205.

Stockton, CW and Jacoby, GC (1975) An overview of the effect of Lake Powell on the Colorado River Basin water supply and environment. Lake Powell Research Project. Bulletin No. 14. University of California, Los Angeles.

Stokes, S, and Gaylord, DR (1993) Optical dating of Holocene dune sands in the Ferris Dune Field, Wyoming. Quaternary Res 39: 274-281.

Stone, JR and Fritz, SC (2006) Multidecadal drought and Holocene climate instability in the Rocky Mountains. Geology 34: 409-412.

U.S. Forest Service (1976) Environmental Statement, North Slope Use Plan. Wasatch National Forest, Intermountain Region, Ogden, Utah.

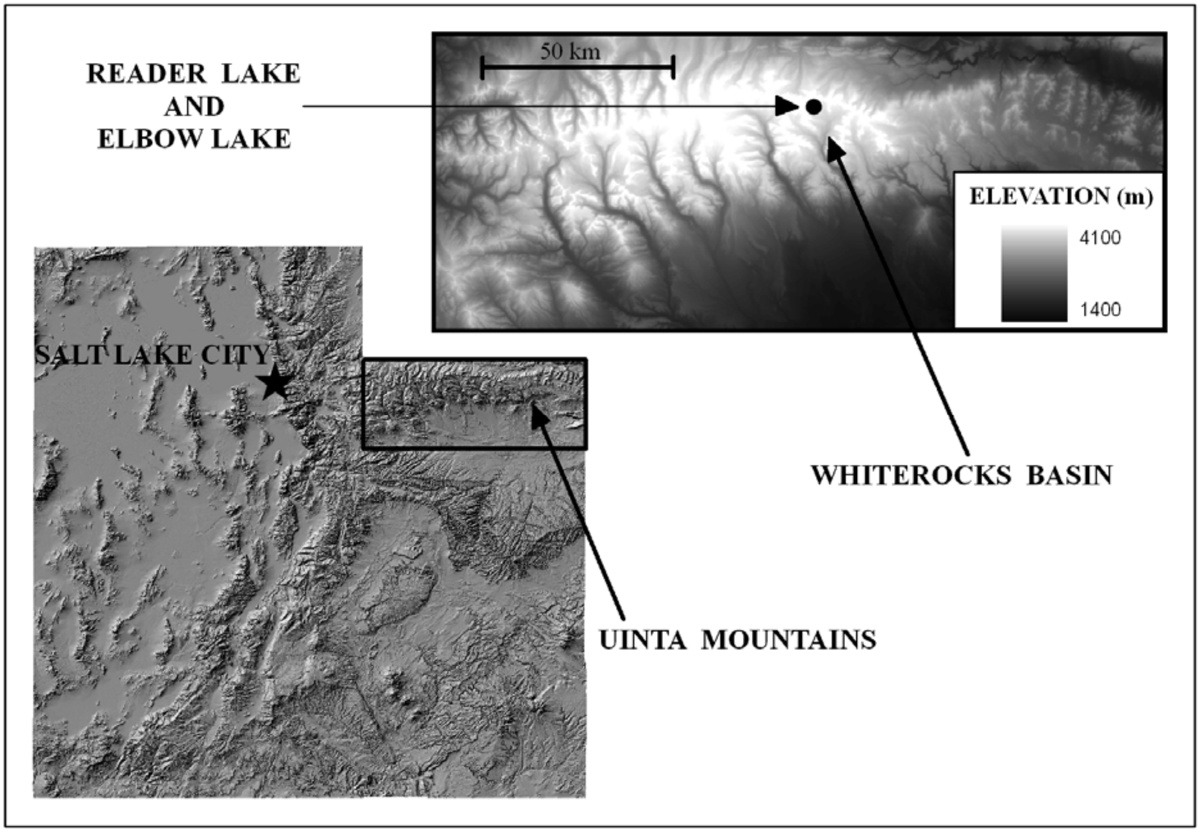
READER LAKE
AND
ELBOW LAKE
50 km
ELEVATION (m)
4100
1400
SALT LAKE CITY
WHITEROCKS BASIN
UINTA MOUNTAINS

Figure 1.

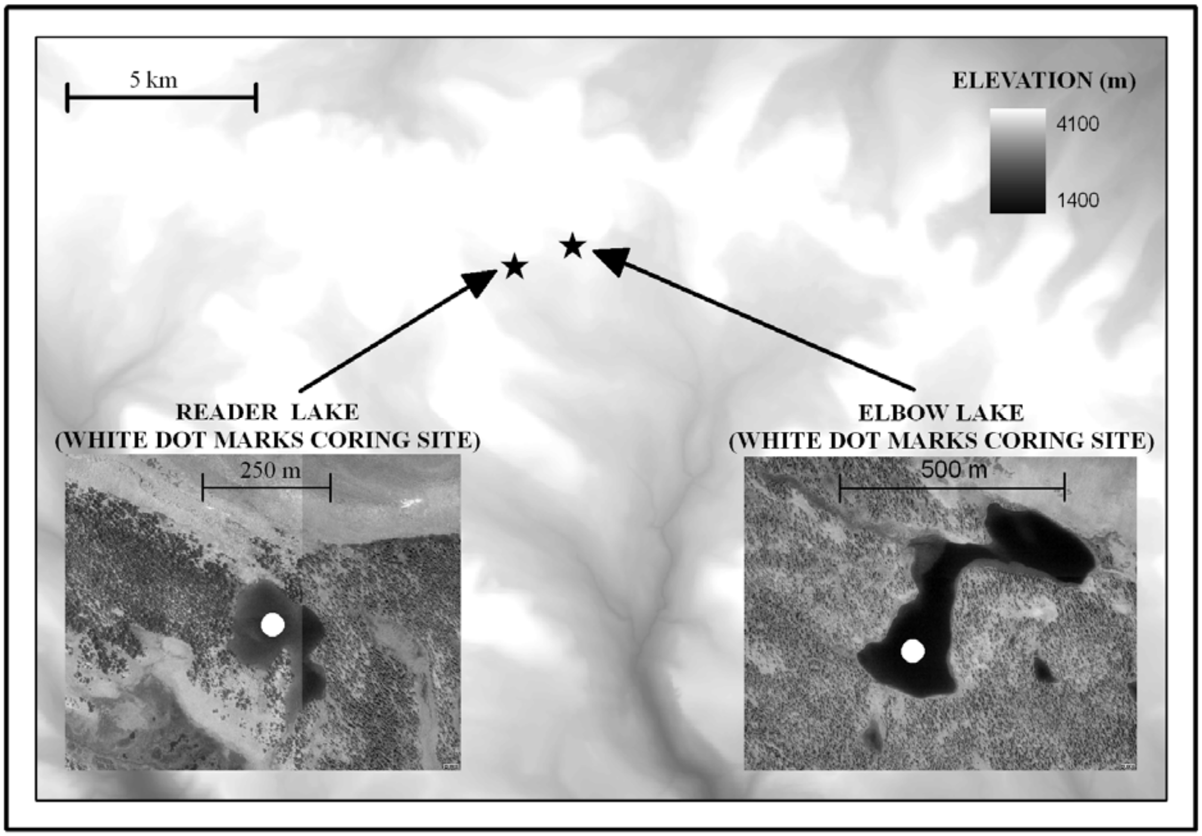
5 km
ELEVATION (m)
4100
1400
READER LAKE
(WHITE DOT MARKS CORING SITE)
250 m
ELBOW LAKE
(WHITE DOT MARKS CORING SITE)
500 m

Figure 2.

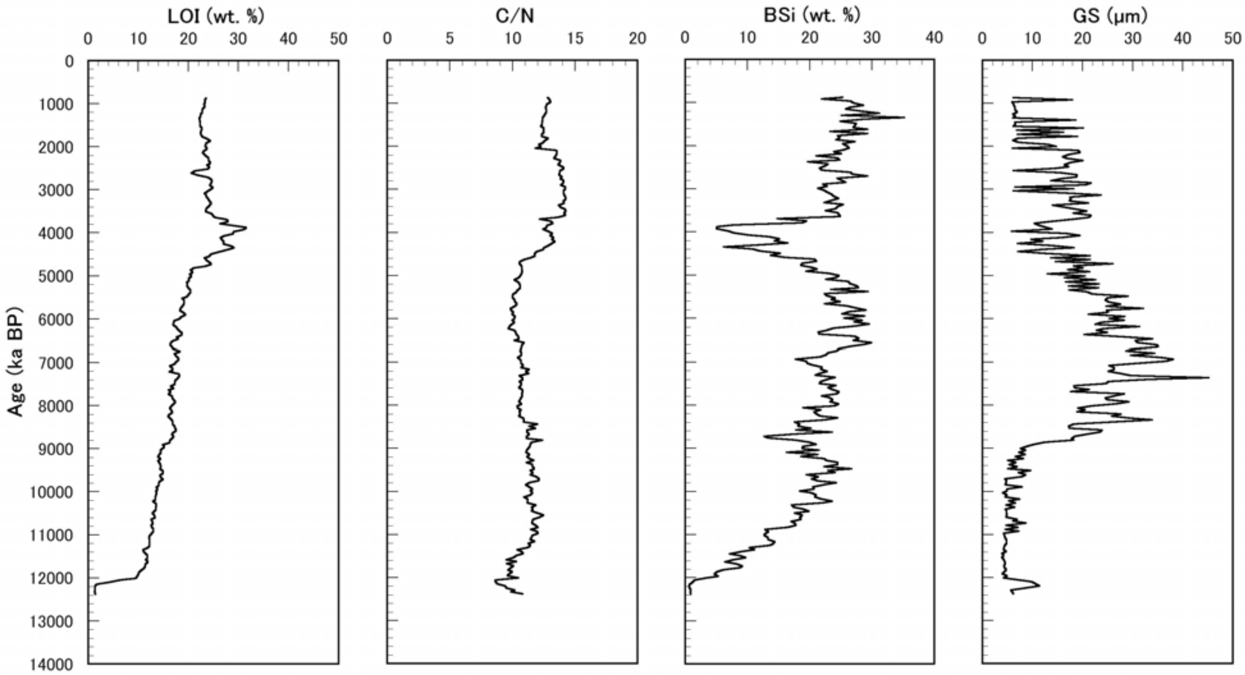

Figure 3.

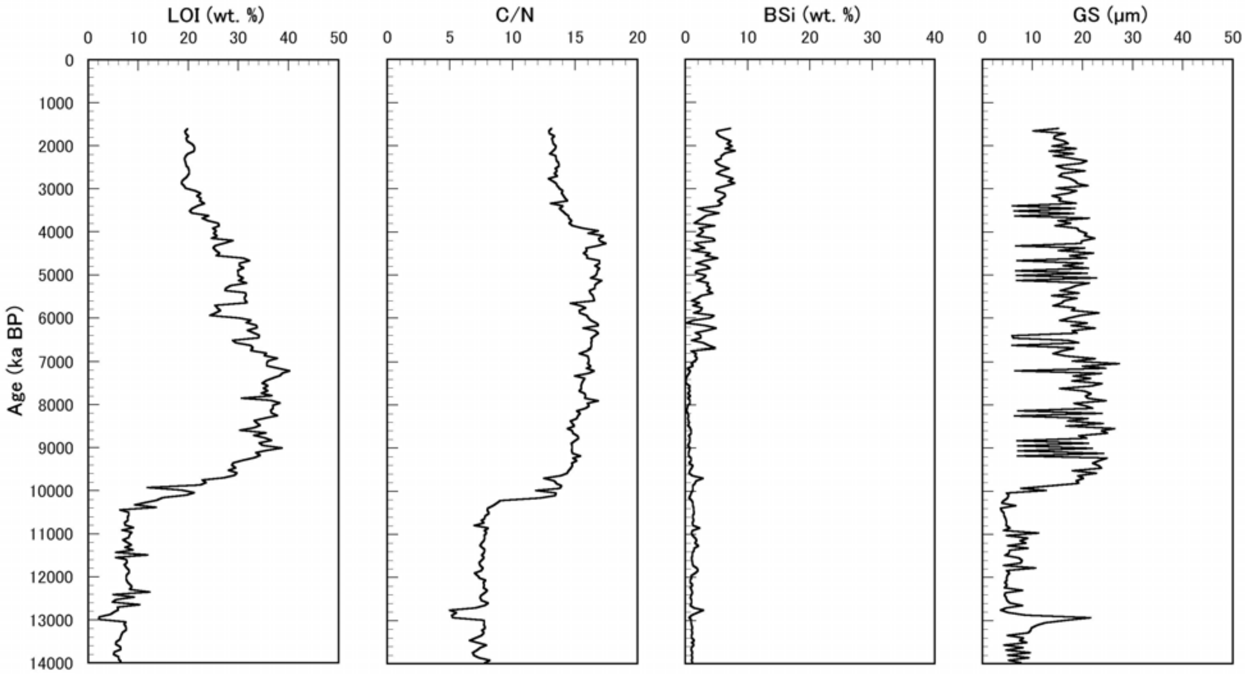
LOI (wt. %)
C/N
BSi (wt. %)
GS (μm)
Age (ka BP)
0 10 20 30 40 50
0 5 10 15 20
0 10 20 30 40
0 10 20 30 40 50
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000 13000 14000

Figure 4.

Figure Captions

Figure 1. Reader Lake and Elbow Lake are located in the southeastern Uinta Mountains of Utah.

Figure 2. 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. Elbow Lake is larger, deeper, and has an active inflow that has created a significant delta in the northwest corner of the lake.

Figure 3. LOI, C/N, BSi, and GS data at 1-cm resolution from the Reader Lake sediment core (total length of 245 cm).

Figure 4. LOI, C/N, BSi, and GS data at 1-cm resolution from the Elbow Lake sediment core (total length of 216 cm).