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A diatom record of late Holocene climate variation in the northern range of Yellowstone National Park, USA

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Abstract

The changes in diatom species composition in a sediment core from Crevice Lake, Yellowstone National Park, spanning the past 2550 yr, were used to reconstruct long-term limnological and ecological conditions that may be related to late Holocene climate variability. Planktic forms dominate the fossil diatom assemblages throughout this record, but changes in species dominance indicate varying nutrient levels over time, particularly phosphorus. The changes in the nutrient concentrations in the lake were probably driven by changes in temperature and wind strength that affected the duration of water-column mixing and thus the extent of nutrient recycling from deep waters. Prior to 2100 cal before present (BP), *Stephanodiscus minutulus* and *Synedra tenera* dominated, suggesting long cool springs with extensive regeneration of phosphorus from the hypolimnion that resulted from isothermal mixing. From 2100 to 800 cal BP, these species were replaced by *Cyclotella michiganiana* and *Cyclotella bodanica*. These species are characteristic of lower nutrient concentrations and are interpreted here to reflect warm summers with long periods of thermal stratification. From 800 to 50 cal BP, *S. minutulus* dominated the diatom assemblage, suggesting a return to lengthy mixing during spring. The most dramatic late Holocene changes in the fossil diatom assemblages occurred during the transition from the Medieval Period to the Little Ice Age, approximately 800 cal BP.

1. Introduction

The Rocky Mountains are the source area for several major western rivers that provide water for cities, agriculture, and transportation systems (Downey and Dinwiddie, 1988; Chagnon *et al.*, 1991). Persistent precipitation deficits in recent years have produced severe water shortages throughout much of the region (Hidalgo, 2004). In addition, warmer winter and spring temperatures have affected the volume of mountain snow pack and the timing of seasonal snowmelt and runoff (Barnett *et al.*, 2005; Mote *et al.*, 2005).

Reconstruction of long-term temperature and precipitation patterns in the Rocky Mountain region using paleoclimatic archives can extend the climate record beyond the instrumental period and aid in our understanding of natural patterns of climatic variation and their environmental impacts (Cook *et al.*, 2004). The Rocky Mountain region has a spatially variable climate, which is the product of the topographic gradi-

ents and the resultant differential heating of mountain slopes, diversion or concentration of winds through mountain passes, precipitation rain shadows, amongst others. Mock (1996) suggests a complex of climatic controls that each modifies different spatial regimes within the mountainous terrain. As a result, sites that are relatively close to one another may not experience the same climate or show the same history, because each may be influenced by a synoptic climatology that is modified by the local topography (Williams *et al.*, 1996). Tree-ring reconstructions are now available for many parts of the Rocky Mountains (e.g. Woodhouse, 2001; Cook and Krusic, 2004; Gray *et al.*, 2004; Gray *et al.*, 2007); however, these records can be corroborated and the history of climatic variation can be extended to longer periods of time using high-resolution analysis of lake sediments.

This study has reconstructed the climate history of the northern portion of Yellowstone National Park at approximately decadal resolution for the past ~2500 yr based on mul-

tiple proxies from Crevice Lake, including pollen, charcoal, geochemical variables, and diatoms (Whitlock *et al.*, 2007). Although other long paleoclimatic records have been generated from the Yellowstone region, nearly all of these are at a much coarser temporal resolution. Details are provided here on the diatom record from Crevice Lake and its environmental controls. In this particular record, the diatoms provide evidence for changes in the duration of summer stratification of the lake, which reflects the seasonal patterns in temperature and wind.

2. Environmental setting

Crevice Lake (lat. 45.000°N, long. 110.578°W, elev. 1713 m) is a closed-basin deep (maximum depth = 31 m) lake in Yellowstone's northern range. Vegetation in the catchment is characterized by an open forest of *Pseudotsuga menziesii*, *Juniperus scopulorum*, and *Pinus flexilis*, as well as steppe dominated by *Artemisia tridentata* and bunchgrasses. The lake's small size (7.76 ha) and moderate depth ($z_{\text{max}} = 30$ m) promote seasonal anoxia that results in the preservation of annually laminated sediments (varves). The lake is alkaline (total alkalinity = 240 mg L⁻¹ CaCO₃, pH = 8.0, conductivity = 620 μS) and mesotrophic (TP = 20 μg L⁻¹; summer Secchi depth = 7.0 m). The lake sits topographically above the Yellowstone River (Figure 1), and the two are separated by glacial till. The river flows north to south, several hundred meters to the west of Crevice Lake, and it is likely that the lake is hydrologically connected to the Yellowstone River. Thus, although the lake has no surface outflow, lake level is thought to be more strongly influenced by the base level of the river than by the seasonal fluctuations in effective moisture (precipitation minus evaporation, $P-E$).

3. Methods

A freeze core and a series of Austrian (piston) cores were recovered from the ice surface from 30 m of water depth in the Crevice Lake Basin in February 2001 (Figure 2). The cores are varved (annually laminated), and each varve consists

Figure 1. Shaded relief view of Montana with the star indicating the approximate location of Crevice Lake (45.00°N, 110.6°W). The inset is an aerial photo showing the lake with the Yellowstone River running to the left.

Figure 2. Bathymetric map of Crevice Lake showing the basin morphometry. The Austrian cores were taken from the deepest part of the lake basin to reduce distortion of sediments. (Figure modified from Yellowstone National Park Service bathymetric map.)

of an organic-carbonate couplet. The freeze core and the piston cores were combined into a continuous sediment sequence based on distinctive sedimentary changes present in the overlapping core sections. The core sequence was subsampled continuously along bedding planes in 2–4 mm intervals, and each segment was homogenized prior to subsampling for diatoms and other proxies. A chronology for the freeze and upper portions of the Austrian core sequence was established using both varve counts and ¹⁴C dates from plant macrofossils. The top of the freeze core represents the year 2000 AD or 0 yr before present (BP). Six AMS ¹⁴C dates were obtained in these core sections, and the ¹⁴C ages were converted to calendar ages with Calib 5.2 (Stuiver *et al.*, 1998) (Table 1). One of these dates was discarded, because the inverted age relative to adjoining samples indicated reworking of the material. Two varve dates plus five radiocarbon dates were fitted with a third order polynomial to create an age model (Figure 3). For the upper 2550 yr BP, the average sample spacing was 7 yr.

Contiguous samples for diatom analyses were taken from the top 80.5 cm of the Austrian cores and the entirety of the freeze core. Samples were treated with cold hydrochloric acid and hydrogen peroxide to digest the carbonate and organic material, respectively. Rinsed samples were dried onto coverslips, and the coverslips were mounted onto slides with a permanent mounting media (Battarbee, 1986). At least 300 diatom valves were counted on each slide.

Species percent abundances were plotted against the developed chronology to determine the changes in the species abundances during the last 2550 yr. Shifts in the dominant species were used to create a zonation scheme for the diatom stratigraphy, because cluster analysis techniques did not prove useful in determining the zone boundaries.

Table 1.

Radiocarbon ages and the calibrated age equivalents used in constructing the Crevice Lake age model

Sample ID	¹⁴ C lab#	Composite depth (cm)	Material	¹⁴ C age (yr BP)	Age error (yr)	Calibrated range 2 sigma (cal BP)	Midpoint (cal BP)
CV-25	WW-4618	20.45	Needle	210	55	59–320	190
CV-108/109	WW-4619	49.45	Needle	1010	55	791–1010	900
CV-148	WW-4625	63.3	Needle	1610	120	1298–1741	1529
CV-184	WW-4626	75.85	Needle	1920	120	1562–2149	1855
CV-213 ^a	WW-4620	83.85	Bark	2390	45	2337–2519	2428
CV-272	WW-4621	104.15	Needle	2500	80	2362–2742	2552

Samples for radiocarbon dating were prepared in the USGS ¹⁴C laboratory in Reston, VA, and analyzed at the Lawrence Livermore National Laboratory (CAMS).

^a Not used in the construction of the age–depth model.

Figure 3. Age–depth relationship for Crevice Lake (see text for details).

4. Results

The sampled portions of the core consisted of dark to light brown laminated gyttja with intermittent nodules. Few distinct color changes were noticeable along the sequence. The laminations are extremely fine couplets, averaging less than 0.3 mm in thickness, and are likely varves, based on a comparison of counts of couplets and the calibrated ¹⁴C ages. The ¹⁴C ages are used in combination with the varves, because the thinness limits confidence in identifying all the varves.

A zonation scheme for the diatom stratigraphy was constructed based on the changes in the abundance patterns of the four dominant species, *Stephanodiscus minutulus*, *Cyclotella bodanica*, *Cyclotella michiganiana*, and *Synedra tenera* (Figure 4). The determination of the sub-zones within zone 2 was based upon whether or not *C. michiganiana* consistently reached 20% abundance. The divisions within zone 3 were based on the rapid alterations in dominance between *S. minutulus* and *C. bodanica*.

Zone 1 (2550–2100 cal BP) (Figure 4) is characterized by *S. minutulus* and *S. tenera*. Zone 2 (2100–800 cal BP) con-

sists of seven sub-zones. Sub-zone 2A is dominated by *C. bodanica*, with occurrences of *C. michiganiana* that rarely exceed 20% (2100–1550 cal BP). Benthic diatoms are abundant during this zone. Sub-zone 2B (1550–1390 cal BP) is characterized by higher abundances of *C. michiganiana* (40–75%), although *C. bodanica* remains prominent during this period. During the deposition of sub-zone 2C (1390–1300 cal BP), *C. bodanica* returns to dominance (80–90%) with a sudden decrease in *C. michiganiana* (5%). The abrupt dominance (40–60%) of *C. michiganiana* characterizes sub-zone 2D (1300–1290 cal BP). The absence of *C. michiganiana* and the dominance of *C. bodanica* (79–90%) distinguish sub-zone 2E (1290–1050 cal BP). After this period, *C. michiganiana* again exhibits spiky dominance (1050–920 cal BP), which defines sub-zone 2F. The last sub-zone, 2G (920–800 cal BP), is defined by the dominance of *C. bodanica* and almost complete disappearance of *C. michiganiana*.

Zone 3 has three major sub-zones. During the first sub-zone, 3A (800–245 cal BP), *S. minutulus* dominates, but *C. bodanica* is still prominent. In sub-zone 3B (245–150 cal BP), *S. minutulus* drops sharply in abundance, while *C. bodanica* dominates. In the most recent sub-zone, 3C (150–0 cal BP), both *C. bodanica* and *S. minutulus* are the most common taxa, but shifts in abundance occur very rapidly throughout this period. *Fragilaria capucina* is also prominent during this interval, but this species never dominates the assemblage.

5. Discussion

5.1. Diatom paleoecology

The dominant feature of the Crevice Lake diatom record is the alternation in dominance between *S. minutulus* and *C. bodanica*. Modern ecological data from surface-sample calibrations consistently show that *S. minutulus* is characteristic of higher phosphorus conditions than *C. bodanica*. For example, in eastern Canada the phosphorus optimum for *C. bodanica* is 10.0 µg L⁻¹, while *S. minutulus* has an optimum of 13.9 µg L⁻¹ (Reavie *et al.*, 1995). In the Yellowstone region, phosphorus is abundant in the andesitic soils that are characteristic of the northern range (Theriot *et al.*, 1997). However, the inter-annual variations in phosphorus supply to planktic

Figure 4. Zonation scheme for approximately the past 2550 yr. Species relative percent abundance are plotted against time (cal BP). The white (blue) designates when *Stephanodiscus minutulus* dominates, but *Synedra tenera* is abundant (zone 1). The dominance of *C. bodanica* is the medium gray (purple) (zone 2, sub-zones 2A, 2C, 2E, and 2G; zone 3, sub-zone 3B). The lightest gray (green) shade denotes the dominance of *S. minutulus* (zone 3, sub-zones 3A and 3C). *C. michiganiana* occurrences of greater than 20% are the darkest gray (yellow) (zone 2, sub-zones 2B, 2D, and 2F).

diatoms in Crevice Lake are most likely related to changes in water-column mixing and internal regeneration of phosphorus, rather than supply from the lake catchment (Theriot *et al.*, 1997; Interlandi *et al.*, 1999). During mixing, phosphorus is regenerated from the hypolimnion, which creates conditions favorable for species that can utilize the nutrient quickly or that require high phosphorus concentrations to flourish, such as *S. minutulus* or *S. medius*. Once mixing has ended, and

stratification occurs, the lower phosphorus concentrations in the epilimnion favor *C. bodanica*.

Based on this model, the prominent fluctuations in the dominance between *C. bodanica* and *S. minutulus* likely reflect changes in lake water chemistry that are associated with the duration of isothermal mixing in spring relative to periods of thermal stratification in summer. *C. bodanica* blooms when phosphorus is in low supply, nitrogen is relatively

abundant, and overall phytoplankton biomass is low (Interlandi *et al.*, 1999). In the Yellowstone region lakes, it is most common in the summer months during times of water-column stratification. It often forms a layer of cells near the thermocline, where nitrogen is higher in concentration than in the rest of the water column. *S. minutulus* populations are characteristic of low N:P and Si:P ratios, and this species blooms, in Yellowstone lakes, in early spring during times of isothermal mixing (Kilham *et al.*, 1996; Interlandi *et al.*, 1999). Because *S. minutulus* and *C. bodanica* bloom during two different times of the year, spring and summer, the two species are never in direct competition for nutrients. Nonetheless, large *S. minutulus* blooms during spring mixing may remove sufficient phosphorus and other micronutrients from the water column. Nutrient availability is then reduced for subsequent algal species, such as *C. bodanica*, which prevents them from blooming in the summer months. Conversely, if spring mixing is incomplete or truncated, *S. minutulus* may remove less phosphorus from the system, allowing larger populations of species that bloom later in the summer. In northern Minnesota, a similar combination of water-chemistry and stratification conditions was observed in association with these taxa. Using data from seasonal traps in Elk Lake, MN, Bradbury (1988) found that *S. minutulus* bloomed during the spring mixing season and declined rapidly during the onset of summer stratification, while this stratification was required for the dominance of *C. bodanica*.

The correspondence of *S. minutulus* and *C. bodanica* with nutrient variability that is strongly associated with seasonal differences in the length of the period of isothermal mixing relative to the period of stratification suggests that their abundance is linked to climatic drivers that control the lake thermal structure (Bradbury, 1988). Various factors, such as thin ice cover, early cool windy springs, and delayed summer warming, contribute to protracted periods of deep water circulation (Bradbury, 1988). Under these conditions, species assemblages with high nutrient requirements, such as *S. minutulus*, should dominate longer into the summer months (Kilham *et al.*, 1996).

Shifts in some of the sub-dominant species, such as *Asterionella formsosa* and *S. tenera*, are also likely related to changes in the lake thermal structure. Both the species are extremely efficient under low-phosphorus conditions and, in the Yellowstone region lakes, increase in relative abundance after *S. minutulus* blooms (Interlandi *et al.*, 1999) but prior to the onset of stratification. Thus, these species may be indicative of years of particularly long periods of isothermal mixing.

Little is known about the specific nutrient requirements of *C. michiganiana* or *Cyclotella ocellata* relative to *C. bodanica*, although overall these *Cyclotella* species also are characteristic of lower phosphorus concentrations than *Stephanodiscus* spp. We speculate that these taxa bloom under conditions of more protracted summer stratification (with *C. ocellata* blooming under the most N-limiting conditions) than *C. bodanica*.

The dominant influence of thermal stratification on the diatom assemblages in the Crevice Lake record is corroborated by the stratigraphy of other proxies analyzed from the same sequence (Whitlock *et al.*, 2007). For example, redox-sensitive elements, such as sulfur, show patterns of change similar to those observed in the diatom record. Thus, the duration of summer stratification affects the oxygen concentrations at the sediment water interface and the solubility and the phase of redox-sensitive elements. In contrast, the pollen and the charcoal reconstructions show little direct relationship to the higher frequency changes in the diatom record, suggesting that variation in vegetation and fire are not likely drivers of changes in the limnological environment.

Amphora pediculus, which is epiphytic, is the most common benthic species in the upper Crevice Lake sediments. Increases in its abundance probably reflect increased macrophyte growth, possibly associated with years of high light penetration because of the reduced phytoplankton biomass. Overall benthic species are rare in the Crevice Lake stratigraphic record, likely because of the high productivity of planktic diatoms, which reduced the proportion of benthic diatoms in the sediments. In addition, most of the lake is moderately deep, even the shelf area at the southwest margin of the lake (Figure 2).

5.2. Implications for paleoclimate history

The dominance of *S. minutulus* in sub-zones 3A (800–245 cal BP) and 3C (150–0 cal BP) in the upper portion of the core, as well as in zone 1 (2550–2100 cal BP) suggests periods of extended water-column mixing produced by long, cool, windy springs. Sub-zone 3B (245–150 cal BP) has lower proportions of *S. minutulus*, than the intervals immediately before or after, which suggests that the spring season was milder and/or shorter such that the onset of stratification was earlier in the year.

The absence of *S. minutulus* and *S. medius* from the diatom record between 2100 and 800 cal BP suggests that the spring mixing season was short during this time, probably because of warmer spring and summer temperatures that produced extended summer stratification. This inference is corroborated by an increase in pyrite and other redox-sensitive elements at the same time (Whitlock *et al.*, 2007). Fluctuations in dominance between *C. michiganiana* and *C. bodanica* in this zone are thought to reflect changes in the nutrient concentrations and the length of the stratified period, but the exact interactions between these two species are not known.

Benthic diatoms, which grow in shallow water, persist at low levels between 2550 and 800 cal BP, with highest abundance at 1900 cal BP. Because of Crevice Lake's morphometry, an increase in benthic diatom abundance does not necessarily imply that lake levels decreased (Stone and Fritz, 2004). The lake has a broad shelf, but it is moderately deep (Figure 2). Moreover, lake-level changes are likely most strongly influenced by groundwater interactions with the nearby Yellow-

stone River; porous glacial till separates the lake basin from the river, and this connection would act as a buffer against the drastic water level changes caused by drought (Almendinger, 1990). Given these constraints, the increased abundance of benthic diatoms probably reflects times when high water clarity maximized benthic diatom growth. In this case, the coincidence of increased benthic diatom abundance with times of prolonged summer stratification likely reflects high water clarity. This is consistent with the low summer nutrient concentrations in the epilimnion, as suggested by the dominance of *Cyclotella* species (see above), and with limnological studies of modern Yellowstone lakes that show high Secchi depth during times of summer stratification (Interlandi *et al.*, 1999).

5.3. Comparison to regional records

Several reconstructions of late Holocene climatic conditions are available for the Yellowstone region. Mammalian fossil records show some similarity in trends to the patterns evident in the Crevice Lake diatom record, particularly a more mesic faunal assemblage between 700 and 100 cal BP than during the previous times (Hadley, 1996). The onset of this major change roughly corresponds to the warmer springs inferred in the Crevice record prior to 800 cal BP. Fire-frequency records are influenced by and respond to climatic drivers similar to those that affect lake stratification patterns, and these records are often sampled at similar scales. Meyer *et al.* (1992) suggest that fire frequency was influenced by drier summers during the time spans 2800–1650 and 1000–750 cal BP, with the maximum number of fires during the Medieval Climatic Anomaly (1000–800 cal yr BP). Other regional fire records, based on the analysis of lake cores, show broad-scale similarities, in that they show evidence for cooling during the Little Ice Age interval and warming during the Medieval Climatic Anomaly (Pierce *et al.*, 2004).

Several paleoclimatic records within Montana show large-scale changes with the same timing as those in the diatom record from Crevice Lake. Tree-ring reconstructions from northern Yellowstone National Park show major droughts in the 13th century, as well as in the mid-18th through mid-19th centuries (Gray *et al.*, 2007), which roughly correspond to changes within the Crevice Lake diatom record. This suggests that the climate changes at these times may have affected both temperature seasonality and precipitation. The diatom record from Foy Lake, in northwestern Montana, shows little similarity to the Crevice Lake record, because it records primarily changes in *P-E* (Stevens *et al.*, 2006; Stone and Fritz, 2006). In contrast, major shifts in the vegetation and fire history of Foy Lake (Power *et al.*, 2006), which are interpreted to reflect temperature changes during the spring and summer growing season, occur at 2125 and 750 yr BP, similar in timing to the major shifts in the Crevice Lake diatom record. The higher frequency shifts within the Crevice Lake diatom record, however, are not evident in the Foy Lake pollen record, probably because of its coarser resolution.

Dendrochronology from tree kill dates suggests that glacial advances occurred at 850–650, 754–625, 300–275, and 175–150 cal BP (adjusted from AD dates) in the southern Canadian Rockies (Luckman, 2000). The major shift in diatom species abundance indicative of cooler springs occurs in the 850–650 cal BP interval, but this is the only consistent period of positive correlation between the two data sets. The intervals 300–275 and 175–150 cal BP correspond to spikes in *C. bodanica*, but several other increases of similar magnitude occur that do not correspond to glacial advance. Therefore, a consistent correlation does not exist between these two records. The sites used for the dendrochronological study are between 50°N and 54°N, while Crevice Lake is at 45°N, and thus the differences in the reconstructed climatic histories may result from differences in the relative synoptic climatology. Additionally, the two records are not necessarily recording the same type of climate signal. Glacial advances imply cooler summer temperatures, which may or may not be well connected with the spring conditions that influence lake stratification. Overall, however, the glacial advances and cooling inferred from the Crevice Lake diatom record occurred during the Little Ice Age interval, which persisted from approximately 800–150 cal BP (Luckman, 2000). Subsequently, glaciers retreated toward their present-day positions.

The climate shift that affected the Yellowstone region at roughly 800 cal BP is evident in many parts of western and central North America (Woodhouse and Overpeck, 1998; Laird *et al.*, 2003; Goble *et al.*, 2004; Booth *et al.*, 2006), which suggests that changes in Pacific and/or Atlantic sea-surface temperatures altered the atmospheric circulation patterns across North America. In addition, there is more limited evidence for a major climatic shift at roughly 2100 cal BP (Laird *et al.*, 1996; Anderson *et al.*, 2005; Denniston *et al.*, 2007; Miao *et al.*, 2007), which also may reflect a large-scale change in the continental circulation.

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