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A 2650-year-long record of environmental change from northern Yellowstone National Park based on a comparison of multiple proxy data

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A 2650-year-long record of environmental change from northern Yellowstone National Park based on a comparison of multiple proxy data

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Abstract

Geochemical, stable-isotope, pollen, charcoal, and diatom records were analyzed at high-resolution in cores obtained from Crevice Lake, a varved-sediment lake in northern Yellowstone National Park. The objective was to reconstruct the ecohydrologic, vegetation, and fire history of the watershed for the last 2650 years to better understand past climate variations at the forest-steppe transition. The data suggest a period of limited bottom-water anoxia, relatively wet winters, and cool springs and summers from 2650 to 2100 cal yr BP (700–150 BC). Dry warm conditions occurred between 2100 and 850–800 cal yr BP (150 BC and AD 1100–1150), when the lake was anoxic, winter precipitation was low, and summer stratification was protracted. The data are consistent with overall warmer/drier conditions during the Medieval Climate Anomaly, although they suggest a shift towards wetter winters within that period. The period from 850 to 800 cal yr BP (AD 1100–1150) to 250 cal yr BP (AD 1700) was characterized by greater water-column mixing and cooler spring/summer conditions than before. In addition, fire activity shifted towards infrequent large events and pollen production was low. From 250 to 150 cal yr BP (AD 1700–1800), winter precipitation was moderate compared to previous conditions, and the lake was again stratified, suggesting warm summers. Between 150 and 42 cal yr BP (AD 1800–1908), winter precipitation increased and spring and summer conditions became moderate. Metal pollution, probably from regional mining operations, is evident in the 1870s. Large fires occurred between ca. 1800–1880, but in general the forests were more closed than before. The Crevice Lake record suggests that the last 150 years of Yellowstone’s environmental history were characterized by intermediate conditions when compared with the previous 2500 years.

1. Introduction

The northern part of Yellowstone National Park (YNP) is a mixture of steppe and forest within the Lamar River and Yellowstone River watersheds. This region is called the northern range, because it is the historic winter range of Yellowstone’s elk and bison herds. Since the 1960s, when the park adopted a management policy of natural regulation, claims have been made that the northern range has been overgrazed and riparian communities have been deteriorating as a result of heavy ungulate winter use. In 1998, the US Congress directed the National Park Service (NPS) “to initiate a National Academy of Sciences review of all available science related to the management of ungulates and the ecological effects of ungulates on the range land of YNP and to provide recommendations for implementation by the Service”. The final report of this...
review was published in 2002 by an interdisciplinary panel of scientists (National Research Council, Committee on Ungulate Management in Yellowstone National Park, 2002). Among the findings was that northern YNP lacked sufficient paleoecological data to document the range of historical environmental variability and identify particular ecological attributes that might signal unacceptable conditions. A recommendation was that more research was needed to fully assess natural variation and to better link past and present processes in the region.

This mandate motivated the study of sediment cores from Crevice Lake (lat. 45.000N, long. 110.578W, elev. 1713 m), a closed basin at the lower forest/steppe border in the canyon of the Yellowstone River in northern YNP (Fig. 1). Its limited surface area (7.76 ha), conical bathymetry, and deep water (>31 m) create anoxic conditions that preserve annually laminated sediments (varves). The Crevice Lake drainage basin currently supports open forests of Pseudotsuga menziesii, Juniperus scopulorum, and Pinus flexilis, as well as steppe dominated by Artemisia tridentata and bunchgrasses. At higher elevations, Pinus contorta, Abies lasiocarpa, and Picea engelmannii become abundant. A rocky scree slope is present along the northern side of the watershed, but most of the catchment is vegetated. Betula occidentalis, Alnus incana, and Salix spp. grow in moist settings, and Carex, Scirpus, and Typha latifolia are present along the lake margin.

To gain an understanding of the climatic and ecohydrologic history of the northern range, we examined the last 2650 years of the Crevice Lake record. Sediment cores were collected from the ice surface in February 2001 with Livingstone and UWITEC percussion coring systems, as well as a freeze-box corer. Two overlapping Livingstone cores and four overlapping UWITEC cores were retrieved, split longitudinally, and photographed at 10 cm intervals. The photographs provide an archive of sample locations and thicknesses, macrofossil locations, and general sedimentary changes. Several distinct marker beds allowed easy correlation of cores. The Livingstone cores were archived and sampling was done on the 8-cm-diameter UWITEC cores and the freeze cores.

Several data sets were examined in this study. Core lithology and elemental geochemistry were analyzed to document erosional inputs, changes in water chemistry, and variations in bottom-water oxygen conditions. Geochemical data helped to identify the major sediment components as detrital rock debris, endogenic CaCO₃, organic matter, and biogenic silica (diatom remains). Fossil diatoms provided a proxy of lake stratification, nutrient status, and timing of ice-off. Variations in the abundance of macroscopic charcoal particles indicated past changes in fire activity in the watershed. Fossil pollen data revealed the nature of past vegetation and changes in pollen production related to conditions during the flowering season.

2. Chronology and sampling strategy

An age model was constructed from a combination of accelerator mass spectrometer (AMS) radiocarbon dates (Table 1) and varve counts. AMS radiocarbon ages were obtained from six plant macrofossils from the upper 1.1 m of the UWITEC core, although one was excluded from the age model (see Stevens and Dean, this volume). Samples were prepared in the USGS ¹⁴C laboratory in Reston, Virginia, and the dating was done at the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory in Livermore, California. Radiocarbon ages were calibrated with the CALIB 5.2 program (Stuiver et al., 1998), and calibrated ages are listed in Table 1 as cal yr BP (before AD 1950) and plotted as cal yr BP and BC/AD. A third-order polynomial fit to the depth and age data (Fig. 2) provides the best estimate of the age/depth relations.

The UWITEC cores were sliced along bedding planes at 2–4 mm intervals over the upper 112 cm, and the number of laminations was counted three times to produce a varve chronology. The average sample was 3 mm thick and represented an average of 7 years, and there was no trend in varve number cm⁻¹ through the length of the record. Contiguous samples were analyzed for magnetic properties, stable isotopes, carbons, charcoal, and diatoms. The freeze core was analyzed for pollen and isotopes and so those records extend to present day; other analyses focused on the UWITEC core and extend to 42 cal yr BP (AD 1908). Major- and trace-element geochemistry was done on...
every other sample, and XRD was measured on every eighth sample. Pollen samples were spaced 5–7 cm apart, representing ca. 20–45-yr intervals. This sampling resolution allowed us to look at variability occurring on multidecadal and longer time scales.

3. Analytical methods

3.1. Geochemistry and magnetic susceptibility

Concentrations of total carbon (TC) and total inorganic carbon (TIC) were determined by coulometric titration of CO₂ following extraction from the sediment by combustion at 950 °C and acid volatilization, respectively (Engleman et al., 1985), in the USGS laboratories, Denver CO. Weight percent TIC was converted to weight percent CaCO₃ by dividing TIC by 0.12, the fraction of carbon in CaCO₃. Total organic carbon (TOC) was determined as the difference between TC and TIC. The accuracy and precision for both TC and TIC, determined from hundreds of replicate standards (reagent-grade CaCO₃ and a Cretaceous OC-rich marlstone), were usually better than 0.10 wt%. Two standards were run at the beginning of each sample run and one at the end.

Samples were analyzed for 40 major, minor, and trace elements by inductively coupled plasma-mass spectrometry (ICP-MS) by SGS Minerals Services, Toronto, Canada. Rock standards (USGS) were included with the sediment samples, and 5% of the samples were analyzed in duplicate. The precision, determined by analyzing rock standards and duplicate sediment samples, was better than 10% and usually better than 5% at a concentration of 10 times the limit of detection.

For magnetic susceptibility (MS) measurements, samples were placed in nonmagnetic 3.2-cm³ plastic boxes. MS values, which were acquired after drying to eliminate the diamagnetic effects of pore water, were measured in a 600-Hz alternating field with amplitude of about 0.1 mT. The MS readings were corrected for the diamagnetic effect of sample boxes.

3.2. Stable isotopes

Stable isotopic measurements were undertaken on bulk sediment that had been pretreated and sieved to remove organic matter and shells (see Stevens and Dean, this volume). Isotopic measurements were made on a Finnigan MAT 252 mass-spectrometer coupled to a Kiel II carbonate sampling device at the University of Minnesota, Minneapolis. Results are reported in the usual per mil (‰) δ—notation relative to the Vienna Pee Dee Belemnite (VPDB) marine-carbonate standard for carbon and oxygen:

\[ \delta^{18}O = \left( \frac{R_{\text{sample}}}{R_{\text{VPDB}}} - 1 \right) \times 10^3, \]
where $R$ is the ratio ($^{13}$C:$^{12}$C) or ($^{18}$O:$^{16}$O). Reproducibility for both oxygen and carbon was 0.06‰.

### 3.3. Diatoms

Samples for diatom analysis were treated with cold 10% hydrochloric acid and hydrogen peroxide to remove carbonates and organic matter, respectively (see Bracht et al., this volume). Samples were rinsed, dried onto coverslips, and the coverslips mounted on slides with Zrax, a permanent mounting medium. At least 300 individuals were identified and counted in each sample. Diatom counts are expressed as percentages relative to the total number of individuals counted in each sample.

### 3.4. Pollen

Fifty-nine pollen samples were prepared using standard procedures (Faegri et al., 1989), and Lycopodium spores were added to enable calculation of pollen concentration. About 300–500 terrestrial pollen grains were counted for each level, and pollen percentages were based on the sum of terrestrial pollen and spores. Diploxylon-type *Pinus* pollen is referred to *Pinus contorta*, and haploxylon-type *Pinus* is attributed to *P. flexilis*, which grows locally, but *P. albicaulis* from higher elevations in YNP may also have been a minor pollen source. Total *Pinus* is the sum of the diploxylon-type, haploxylon-type, and pine pollen that could not be differentiated.

The arboreal/nonarboreal ratio is derived from the percentage of tree pollen divided by that of shrubs and herbs. It is used as a proxy of forest cover relative to steppe cover (Whitlock, 1993). Pollen concentration was divided by the deposition time (number of years/sample) to calculate pollen accumulation rates (PAR, grains cm$^{-2}$ yr$^{-1}$). Because the usual uncertainties of deposition time were mitigated by varve counts, changes in PAR through time were considered a reasonable record of pollen production in the watershed (see Faegri et al., 1989 for interpretation of PAR).

### 3.5. Charcoal

Macroscopic sedimentary charcoal was sampled from the freeze core (~1 mm intervals averaging 0.97 years) and long core (~3–5 mm intervals). Samples for charcoal were disaggregated in hot 5% KOH for 10–20 min and gently washed through a 125-μm-mesh screen. Charcoal particles (> 125 μm in minimum diameter) were tallied at 36X on a dissecting microscope. Charcoal counts were converted into charcoal concentration (particles cm$^{-3}$) and the data were binned into 10-year intervals. Charcoal accumulation rates (CHAR, charcoal particles cm$^{-2}$ yr$^{-1}$) were created by interpolating charcoal concentrations by multiplying the average charcoal concentration for each bin by the interpolated sedimentation rate for the period of time represented by each bin.

A decomposition technique, described in Long et al. (1998), was used to separate the CHAR data into two components, background and peaks. The background component likely reflects long-term changes in biomass or the occurrence of regional fires. The peaks component, or large positive deviations of CHAR above the background component, likely reflects fire episodes in the catchment of the lake during the time span of the sample, 1.3 years for the freeze core and 5 years for the long core. The background component was determined using a locally weighted moving average of 150 years. Fire episodes or “peaks” were identified when CHAR exceeded the background CHAR by a prescribed threshold ratio of 1.10. The threshold ratio was selected based on comparison of CHAR peaks with known fire dates from tree-ring studies in the watershed (Littell, 2002). The number of charcoal peaks/1000 yr, referred to as the fire-episode frequency, was calculated by smoothing the binary fire-episode series with a 1000-year moving window width to graphically display variations in the frequency of fire episodes.

### 4. Results and discussion

#### 4.1. Physical limnology

The sediment consisted of four-components: (1) detrital rock debris (inferred from Al and Ti in Fig. 3(A), for example); (2) endogenic CaCO$_3$ as calcite (Fig. 3C); (3) organic matter (Fig. 3F); and (4) biogenic silica (diatom remains) (not shown).

A record of detrital influx into the lake is provided by elemental chemistry (Fig. 3). Aluminum (Al) and Titanium (Ti) are good measures of detrital input because their concentrations are not affected by weathering and post-depositional alteration. With the exception of several spikes, Al and Ti contents varied by a factor of less than 2, and averaged about 1.5% and 0.072%, respectively. Assuming that the rock debris in Crevice Lake sediments has the elemental composition of average continental crust (7.8% Al and 0.42% Ti), the sediment in Crevice Lake contains about 18% detrital rock debris on average.

The remaining components were primarily endogenic and exhibited large variations in relative amounts (Fig. 3). TOC, which we assumed is the result of primary production in the lake, averaged about 10%. Organic matter, which typically is about twice TOC (Dean, 1999), was therefore about 20% on average. Seasonal organic productivity probably triggered seasonal precipitation of CaCO$_3$ through the photosynthetic uptake of CO$_2$ and the resultant change of surface-water pH. The CaCO$_3$ content varied considerably with a long-term average of about 10%. The sum of the rough approximations for average rock debris, CaCO$_3$, and organic matter was 48%, which left over 50% for biogenic Si. Thus, the average sediment would be classified as an organic-rich calcareous diatomite.

Some elements, such as molybdenum (Mo, Fig. 3H), uranium (U, Fig. 3I), vanadium (V, not shown), and nickel...
(Ni, not shown), are concentrated under oxygen-deficient conditions in organic-rich sediments where sulfate reduction occurs (e.g., Piper and Dean, 2002). The concentrations of U and Mo in the Crevice Lake sediments were positively correlated among themselves and with TOC and sulfur (S) (Fig. 3F and G). Variations in the concentrations of these elements probably reflect changing redox conditions, with higher concentrations reflecting oxygen-deficient conditions (anoxia in the extreme).

Although MS has commonly been used to interpret variations in detrital material in lake sediments, such an interpretation assumes that detrital Fe-oxide minerals are preserved and that authigenic magnetic minerals (e.g., greigite) have not formed. Relatively poor correlation \( R^2 = 0.45 \) between MS and Al concentration indicated that this was not the case for Crevice Lake. The preservation, destruction, and formation of magnetic minerals apparently were highly sensitive to redox conditions and to the availability of sulfate; however, variations in magnetic susceptibility did not correspond with other indicators of redox conditions (e.g., sulfur content and TOC) (Fig. 3G and F). We suspect that variations in

![Fig. 3. Profiles of (A) aluminum (Al) and titanium (Ti), (B) magnetic susceptibility, (C) percent CaCO₃, (D) \( \delta^{18}O \), (E) \( \delta^{13}C \), (F) total organic carbon (TOC), (G) total sulfur (S), (H) molybdenum (Mo), and (I) uranium (U) versus age in samples from a core from Crevice Lake, Yellowstone National Park.](image-url)
susceptibility reflect complex mixtures of magnetic minerals, both remnants of detrital Fe-oxides and possibly variable amounts of authigenic greigite.

Elemental and carbon chemistry data suggest the following sequence of environmental conditions: Prior to 2100 cal yr BP, low concentrations of S, Mo, and U indicate that the bottom waters of the lake were oxygen deficient but probably not anoxic. Organic productivity in the epilimnion was substantial but lower than at present (<9% TOC; Fig. 3F; average of about 14% organic matter). The influx of allogetic inorganic detritus was relatively low (about 13% based on 1% Al; Fig. 3A). CaCO₃ content accounted for about 15% of the total sediment (Fig. 3C), leaving about 60% that must be biogenic silica.

Between 2100 and 800 cal yr BP (150 BC–AD 1150), productivity was high with greater burial of organic matter (about 12% TOC; Fig. 3F). Bottom waters became more oxygen deficient and probably anoxic throughout the year, resulting in enhanced sulfate reduction in the water column as well as in the sediments and the accumulation of higher concentrations of S (as pyrite), Mo, and U (Fig. 3G–I). Pyrite was detected by XRD in sediments deposited from 2100 to 800 cal yr BP (150 BC–AD 1150), with highest concentrations in sediments deposited between 2100 and 1850 cal yr BP (150 BC–AD 100). These corrosive anoxic bottom waters probably dissolved CaCO₃ produced in the surface waters, resulting in very low CaCO₃ content between 2100 and 1350 cal yr BP (150 BC–AD 600) (although a notable high value of CaCO₃ occurred at 1850 cal yr BP [AD 265]) (Fig. 3C). This carbonate-poor, organic-rich sediment was almost black. Also, the amount of detrital clastic material nearly doubled (ca. 26% based on 2% Al; Fig. 3A).

At about 1800 cal yr BP (AD 100), TOC, S, and trace-metal concentrations decreased (Fig. 3F and G), suggesting higher bottom-water oxygen levels and reduced sulfate (lower S, Mo, and U; Fig. 3–I). The amount of detrital clastic material decreased at this time as indicated by a decline in Al to about 1.5% where it remained until about 800 cal yr BP (one exception is a high level of Al at 1357–1377 cal yr BP) (Fig. 3A).

According to the “carbon pump” model of Dean (1999), accumulation of organic matter and CaCO₃ in lake sediments is a delicate balance between production rates in the epilimnion and rates of organic-matter decomposition and CaCO₃ dissolution in the anoxic, low pH hypolimnion and sediments. In general, periods of low CaCO₃ content at Crevice Lake were associated with high levels of TOC, S, and trace metals indicating low redox conditions and CaCO₃ dissolution. However, an increase in CaCO₃ content to >15% between 1350 and 1100 cal yr BP (AD 600–850) occurred when moderate concentrations of TOC, S, and trace metals indicate that bottom waters were still oxygen deficient. This period may have been one of high production of CaCO₃ in the epilimnion that overwhelmed dissolution in the hypolimnion.

A major shift in the overall environmental state of the lake occurred between 850 and 800 cal yr BP (AD 1100–1150). At 850 cal yr BP (AD 1100), concentrations of TOC, S, and trace metals decreased, suggesting increased oxygen in the bottom waters. By 800 cal yr BP (AD 1150), the detrital component (average Al = 1.8%; Fig. 3A) and organic content (average TOC = 10%; Fig. 3F) decreased, and carbonate content increased (average CaCO₃ = 11%, range 5–20%; Fig. 3C).

Concentrations of copper (Cu), lead (Pb), arsenic (As), cadmium (Cd), and tellurium (Te) were also measured (Fig. 4). An increase in As levels (Fig. 4C) from 2150 to 1850 cal yr BP (200 BC–100 AD) (probably co-precipitated with pyrite; G. Breit, USGS, personal communication) was generally coincident with the interval when other geochemical indicators indicate that bottom waters were annually anoxic and sulfidic. There were also brief periods in the last 2000 years when concentrations of Cu, Pb, and Cd in the sediments peaked. We have no easy explanation for these mostly one-sample peaks.

The metal concentrations in Crevice Lake sediments also define the timing of recent air pollution over YNP (Fig. 4). Concentrations of a number of metals commonly associated with ore deposits increased abruptly near the top of the sediment section. The age of the onset of the anthropogenic increase in metals is very close to the beginning of large-scale mining in Utah, Montana, and Idaho in the 1870s. Although the origin of the metals has not been confirmed, the timing of increased metal concentrations suggests that smelters may have thrown material into the atmosphere and winds carried the material to the Crevice Lake area.

4.2. Hydrologic variations

The δ¹⁸O variations (Fig. 3D) are interpreted as a record of hydrologic variability, in which composition of endogenic carbonates is largely influenced by the isotopic composition of the Yellowstone River (Stevens and Dean, this volume). Crevice Lake lies in the canyon of the Yellowstone River and maintains a groundwater connection with it. Close correspondence between the δ¹⁸O values at Crevice Lake and the tree-ring inferred discharge of the Yellowstone River (Graumlich et al., 2003) suggests that δ¹⁸O variations are a response to changes in the amount of spring snowmelt that affects the isotopic composition of the river. In turn, spring snowmelt is a function of winter precipitation at high elevations in YNP. In this model, low (more negative) δ¹⁸O values correspond with winter conditions in general, wetter winters in particular, and possibly periods of low summer evaporation. High (less negative) values probably occurred during periods of low snowpack leading to reduced spring discharge, and/or greater summer evaporation. Negative (wetter) deviations are of shorter duration than positive deviations from the long-term average δ¹⁸O value, suggesting that the lake responds rapidly to wet years. Drought may be poorly
registered in Crevice Lake relative to lakes in the Northern Great Plains (e.g., Fritz et al., 2000; Laird et al., 2003), which are greatly affected by evaporation, because water residence time is short due to flushing by the Yellowstone River.

The CaCO₃ content of the sediments was sufficient for isotopic determinations in the periods from 2650 to 1950 cal yr BP (700 BC–AD 0) and 1380 to 42 cal yr BP (AD 570–1908). The interval from 2650 to 2000 cal yr BP (700–50 BC) exhibited a trend of decreasing δ¹⁸O values, which suggests a steady increase in spring discharge (and winter precipitation). Variations in δ¹⁸O values at multi-centennial frequency occurred in last 1350 cal yr in association with fluctuations in CaCO₃ content, with high values from 1350 to 1100 cal yr BP (AD 600–850), 850 to 700 cal yr BP (AD 1100–1250), 600 to 500 cal yr BP

Fig. 4. Profiles of (A) copper (Cu), (B) lead (Pb), (C) arsenic (As), (D) cadmium (Cd), and (E) tellurium (Te) versus age in samples from a core from Crevice Lake, Yellowstone National Park.

Fig. 5. Pollen record of last 2650 years at Crevice Lake, showing selected taxa, arboreal/nonarboreal pollen ratios, and pollen accumulation rates.

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(AD 1350–1450), and 425 to 42 cal yr BP (AD 1525–1908). Minima of $\delta^{18}O$ occurred at 450, 650, 900, 1050, and 2000 cal yr BP (Fig. 3D), in association with low percentages of CaCO$_3$, and imply that winter precipitation was higher then. These minima were not in association with increases in S, Mo, and U that would indicate oxygen deficiency, which supports the interpretation that the isotopic record is determined by hydrological (i.e., snowmelt) more than limnological (i.e., evaporative) conditions. The correlation of low $\delta^{18}O$ values and low percentages of CaCO$_3$ may have been caused by a reduction in carbonate production during times of high snowmelt and lake flushing rather than by greater dissolution due to anoxia.

The carbon-isotope record from Crevice Lake is relatively invariant compared with the large shifts in the oxygen-isotopic record (Fig. 3E). Although small decreases in $\delta^{13}C$ values occurred during $\delta^{18}O$ minima (at 450, 650, 900, 1050, and 2000 cal yr BP), large shifts were not associated with changes in diatom assemblages or indicators of anoxia.

4.3. Terrestrial ecology

The pollen record shows only minor stratigraphic variations, implying that the overall distribution of forest and steppe has changed little in the last 2650 years (Fig. 5). Pollen percentages were dominated by Pinus (up to 69%), mostly diploxyon P. contorta-type, which is the dominant conifer of middle and high elevations, especially on rhyolite substrates and areas of recent fire. The steady presence of P. flexilis-type pollen (up to 10%) is attributed to locally growing limber pine. Pinus percentages increased slightly in the last 1000 years. Picea and Abies ($\leq$4% each) are ascribed to long-distance transport from more mesic settings at middle and high elevations. Pseudotsuga and Juniperus-type (probably from J. scopulorum) had slightly...
Fig. 7. Profiles of (A) Palmer drought severity index (PDSI), (B) δ¹⁸O, (C) aluminum (Al) titanium (Ti), (D) CaCO₃, (E) total sulfur (S), (F) magnetic susceptibility, (G) Cyclotella michiganiana, (H) Cyclotella bodanica, (I) Stephanodiscus medius and S. minutulus, (J) charcoal accumulation rates, (K) pollen accumulation rates, and (L) ratio of arboreal to nonarboreal pollen versus age in samples from a core from Crevice Lake, Yellowstone National Park. Vertical line in B is the average value of δ¹⁸O (7.35) for samples younger than 1400 cal yr BP. Horizontal lines delineate five important periods discussed in text.
higher values before 1850 cal yr BP (AD 100) (11% and 4%, respectively) and after 300 cal yr BP (AD 1650) (7% and 3%, respectively). Riparian woodland around the lake contributed steady but low amounts of *Alnus* (probably from *A. incana*), *Betula* (from *B. occidentalis*), and *Salix* pollen throughout the record (all <3%). *Populus tremuloides* pollen was present in trace percentages (<2%) in the last 2650 years. *Poaceae* was well represented (up to 12%), with slightly decreasing values towards the top of the record. *Artemisia*, the second most abundant pollen taxa, featured slightly higher percentages in the period before 2000 cal yr BP (150 BC) (up to 27%), and values were lower in the last 500 years (<20%). *Ambrosia*-type, other Tubuliflorae, and Chenopodiinae showed little change.

The gradual increase in arboreal/nonarboreal pollen ratios toward the top of the record and especially after 250 cal yr BP (AD 1700) suggests that forest cover has increased. The recent rise is supported by photo comparisons from YNP that show an expansion of forest and an increase in tree density in the last century (Meagher and Houston, 1998). PAR shows greater variability than the percentage data, and probably reflect interannual changes in pollen production, which in turn were influenced by spring and summer conditions that affect cone production and flowering success. Most taxa, including *Pinus contorta*-type, *Artemisia*, *Pseudotsuga*, and *Poaceae*, registered highest PAR before 2550 cal yr BP (600 BC), between 2150 and 1850 cal yr BP (200 BC–AD 100), and after 350 cal yr BP (AD 1600). A drop in PAR at 800 cal yr BP (AD 1150) suggests cooler spring conditions and poor pollen production.

The charcoal data provide information on past variations in charcoal production (background CHAR) and fire frequency (charcoal peaks) (Fig. 6). Overall CHAR levels increased between 500 and 150 cal yr BP (AD 1450–1800). The CHAR record shows little relation to fluctuations in Al and Ti (Fig. 3A), which suggests that most of the charcoal is from primary fall-out during a fire and not introduced secondarily as a result of slopewash and erosional processes. Trends in background CHAR suggest changes in available fuel biomass associated with either changes in fuel composition (vegetation) or fuel-moisture levels during the fire season. High CHAR thus indicates the occurrence of large or severe fires that led to the production and deposition of charcoal. CHAR levels were low between 2450 and 500 cal yr BP (500 BC–AD 1450), followed by intervals of high CHAR between 500 and 400 cal yr BP (AD 1450–1550). After 300 cal yr BP (AD 1650), CHAR reached the highest values of the record. CHAR values from the freeze core, sampled at ~1-year intervals from AD 1850 to 2001, significantly declined during the 20th century. The increase in CHAR in recent centuries was also noted in another high-resolution charcoal record from the northern YNP, located east of Crevice Lake (Millsapahg et al., 2004), suggesting a regional increase in fire activity.

Fire scars occurring on two or more trees identified local (watershed) fires in AD 1860s and 1870s (Littell, 2002); these known events were also registered as charcoal peaks. Charcoal peaks registered since AD 1890 did not match any known fires, and we suggest that they were extralocal and/or small events. About 320,900 ha of YNP burned in AD 1988 (http://www.nps.gov/yell/naturescience/fire.htm), and small fires in the Crevice Lake watershed were registered by a charcoal peak. Fire-free intervals averaged 75 years, but two long fire-free intervals were noted between 1570 and 1350 cal yr BP (AD 380–600) and 810 and 670 cal yr BP (AD 1140–1280).

### 4.4. Diatom ecology

The diatom record (described in greater detail by Bracht et al., this volume) was dominated by several planktic diatom species that differ in nutrient requirements and seasonality (Fig. 7). *Stephanodiscus minutulus* and *S. mediuous* (Fig. 7I), which were abundant after 800 cal yr BP (AD 1150) and prior to 2100 cal yr BP (150 BC), are characteristic of periods of deep water-column mixing in the spring months (Interlandi et al., 1999), when phosphorus is regenerated from the hypolimnion and available for planktic algae. In contrast, *Cyclotella* species, including *C. bodanica* and *C. michiganiana* (Fig. 7G, H), bloom during summer stratification, when phosphorus is reduced. Thus, alternations between these two groups reflect differences in the length of summer stratification relative to times of spring isothermal mixing. The diatom data suggest that summer warming occurred earlier in the year, or at least that summers were protracted in the interval between 2100 and 800 cal yr BP (150 BC–AD 1150) and 250 and 150 cal yr BP (AD 1700–1800). These earlier dates correspond with the interval of higher concentrations of TOC, S, and trace metals in the sediments and the inference of more-intense seasonal anoxia. They also match periods of high PAR indicating warm spring/summer conditions.

### 5. Conclusions

The paleolimnologic and paleoenvironmental records of the last 2650 years at Crevice Lake disclose climate variations that occurred on multi-decadal to multi-centennial time scales. These low-frequency variations are evidenced by changes in the timing and length of annual stratification, nutrient status of the lake, and strength of seasonal anoxia in the bottom waters, as well as fluctuations in pollen production, forest density, and fire activity (Fig. 7). The proxy data at Crevice Lake and their comparison with Palmer Drought Severity Index (PDSI) reconstructions of the last 2000 years for the region (Cook et al., 2004, Fig. 7A) identify five important periods:

The interval 2650–2100 cal yr BP (700–150 BC) was a period of weakly oxygenated bottom waters at Crevice Lake, based on low sulfur and trace-metal concentrations, high CaCO3 content, and low influx of detrital elastic material. The abundance of *S. minutulus* relative to *C. bodanica* in the diatom record suggests that the length of
the summer stratified period was relatively short. The $\delta^{18}O$
data show a decreasing trend, providing evidence of
increasing winter precipitation during this period. PAR
and CHAR levels were generally low, implying poor
flowering and short fire seasons.

The interval 2100–800 cal yr BP (150 BC–AD 1150) was a
period of year-round anoxia and sulfate reduction that
resulted in minimal CaCO$_3$ deposition from 2000 to
1350 cal yr BP (50 BC–AD 600). We assume that
year-round anoxia was driven by long or intense summer
stratification, indicated by the dominance of C. bodanica in
the diatom flora. Values of $\delta^{18}O$ suggest dry winter
conditions between 1350 and 1100 cal yr BP (AD 600–850), and wetter conditions between 1100 and
850 cal yr BP (AD 850–1100). PAR values were high during
this interval, implying long flowering seasons with abun-
dant cone production, and low CHAR values suggest that
fires were small or of low-severity as a result of wet
conditions.

This interval includes the so-called Medieval Climate
Anomaly (MCA), which has been variously dated between
cia. 1300 and 650 cal yr BP (AD 650–1300) in the western
US and Great Plains (e.g., Case and MacDonald, 2003;
Fritz et al., 2000; Laird et al., 1996; Pierce et al., 2004;
Stevens et al., 2006; Woodhouse and Overpeck, 1998). The
local PDSI data show persistent dry conditions during
1200 and 900 cal yr BP (AD 750–1050), followed by an
interval of alternating wet and dry extremes from 900 to
600 cal yr BP (AD 1050–1350). A tree-ring reconstruction
from the Yellowstone area suggests a period of pronounced
drought in the early 13th century, followed by periods of
moderate drought to the present day (Gray et al., 2007).
The Crevice Lake data suggest a warm interval with dry
 winters between 1350 and 1100 cal yr BP (AD 600–850),
followed by less dry but still warm conditions between 1100
and 850 cal yr BP (AD 850–1100). Other studies in YNP
indicate that trees grew above present-day treeline and fires
were more frequent in the Lamar and Soda Butte drainages
between 1200 and 800 cal yr BP (AD 750–1150) (Meyer
et al., 1995).

In comparison to the preceding interval, geochemical
data indicate that the interval between 800 and
250 cal yr BP (AD 1150–1700) featured less oxygen-defi-
cient conditions in the bottom waters of Crevice Lake. C.
bodanica, the dominant diatom of the previous period, was
replaced by Stephanodiscus medius and S. minutulus, species
indicating that springs became longer or cooler
than before. After 500 cal yr BP (AD 1450), increased
CHAR suggests more fire activity and perhaps larger
events. Decreased PAR suggests cool spring conditions
with poor pollen production. This cool period at Crevice
Lake coincides with a time of decreased fire-related debris
flow activity in northern YNP (Meyer et al.,
1995).

Wet events at 900 cal yr BP (AD 1050) and 650 cal yr BP
(AD 1300) are inferred from the $\delta^{18}O$ minima and
are comparable to wet intervals in the regional PDSI
data and local tree-ring reconstruction (Gray et al.,
2007). A pronounced wet event between 500 and
400 cal yr BP (AD 1450–1550) was not registered in the
PDSI record and is recorded as a dry interval in the local
reconstruction. One explanation for this discrepancy is the
fact that the tree-ring reconstructions are an estimate of
annual precipitation and summer moisture deficits, whereas the $\delta^{18}O$ values of the carbonates are linked to
winter precipitation and spring runoff. The tree-ring
records may be insensitive to winter moisture if summers
were exceptionally dry.

A shift at 800 cal yr BP (AD 1150) toward cooler
conditions in YNP is consistent with other sites that show
a “moisture regime” change in the 12th and 13th century
(e.g., Case and MacDonald, 2003; Stine, 1994; Woodhouse
and Overpeck, 1998). A rise in lake level and more-frequent
fires in northwestern Montana have been attributed to
intermittent, less persistent drought episodes in the region
(Power et al., 2006; Stevens et al., 2006). Cooler conditions
also caused renewed glacial activity in the northern
Rockies (e.g., Carrara, 1987; Luckman, 2000), although
the timing of advances is highly asynchronous across the
region.

The interval 250–150 cal yr BP (AD 1700–1800) featured
high percentages of C. bodanica implying a return to
lengthy summer stratification. Large or severe fires are
inferred from very high levels of CHAR. Increased forest
density is evidenced by high PAR and arboreal/nonarboreal
carbon ratios. Warmer-than-present spring/summers
were probably responsible for changes in paleoecology,
increases in forest cover, and a shift to large infrequent fires
in YNP.

The interval 150–42 cal yr BP (AD 1800–1908) was
marked by an increase in winter precipitation (low $\delta^{18}O$)
at the end of the 19th century, which is also noted in
the tree-ring reconstruction (Gray et al., 2007). Variable
spring and summer conditions are suggested by rapid
shifts between C. bodanica, S. medius, and S. minutulus.
Several fire events recorded by fire-scarrred trees (Littell,
2002) and charcoal peaks between ca. AD 1860–1880
correspond to high levels of CHAR. Fire activity and
CHAR have decreased since AD 1900 with charcoal peaks
recording only extra-local or small fires. Trace-metal
pollution from regional mining operations is also evident
since AD 1870s.

Three points are worth mentioning from this initial
examination of Crevice Lake. First, the physical and biotic
data from the Crevice Lake show considerable variability
in multi-decadal to multi-centennial time scales, but the
resolution of sampling is not adequate to easily identify
higher frequency variability (e.g., ENSO or PDO shifts).
Interpretation of the record is complicated by the
sensitivities of individual proxies to different aspects of
the environment and the likelihood that leads and lags
occurred in their respective responses. As an example, the
pollen data indicate very little change in vegetation over the
last 2650 years, even though the charcoal record suggests
that there were several fire events and possibly a change in
fire severity in the last 500 years. The diatom data show remarkably abrupt shifts that suggest rapid reorganization of the aquatic environment related to the duration and intensity of lake stratification, and these changes in stratification and bottom-water conditions are also reflected in redox-sensitive trace elements. The geochemistry data indicate that the broad period of anoxia, when C. bodanica dominated the diatom flora, eliminated carbonates necessary to measure stable isotopes. The δ18O data seem to record variations in Yellowstone River discharge and snow accumulation at higher elevations in YNP. The MS is governed by a number of variables that are internal and external to the lake. The differences among proxies stress the need for multiproxy comparisons at other sites and a better understanding of the factors that control individual responses.

A second observation is that a multiple proxy approach helps flesh out the environmental history by providing information on conditions during different seasons. At this site, the δ18O record is sensitive to winter precipitation and spring snowmelt, more than summer evaporation, and the CaCO3 reflects the biological productivity of the surface spring snowmelt, more than summer evaporation, and the nates necessary to measure stable isotopes. The C. bodanica data indicate that the broad period of anoxia, reflected in redox-sensitive trace elements. The geochemistry stratification and bottom-water conditions are also registered, namely the increase in metals associated with mining activities beginning in the 1870s. Comparing the environmental history of recent millennia with that occurring on longer time scales as a result of large-scale changes in the climate system is the next step in this investigation.

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