#### CLIMATOLOGY

### Alpine glacier resilience and Neoglacial fluctuations linked to Holocene snowfall trends in the western United States

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Geological evidence indicates that glaciers in the western United States fluctuated in response to Holocene changes in temperature and precipitation. However, because moraine chronologies are characteristically discontinuous, Holocene glacier fluctuations and their climatic drivers remain ambiguous, and future glacier changes are uncertain. Here, we construct a continuous 10-thousand-year (ka) record of glacier activity in the Teton Range, Wyoming, using glacial and environmental indicators in alpine lake sediments. We show that Teton glaciers persisted in some form through early Holocene warmth, likely as small debris-covered glaciers or rock glaciers. Subsequent Neoglacial ice expansion began ~6.3 ka, with two prominent glacier maxima at ~2.8 and 0.1 ka that were separated by a multicentennial phase of ice retreat. Comparison with regional paleoclimate records suggests that glacier activity was dominantly controlled by winter precipitation variability superposed on long-term Holocene temperature trends, offering key insights into western U.S. glacier resilience and vulnerability to future warming.

#### INTRODUCTION

The retreat of glaciers during the past century remains one of the most visible signals of modern climate change (1, 2) and poses urgent questions about the fate of glacier systems worldwide. Glacier retreat affects the storage and release of freshwater (3) with local- to global-scale consequences, including water resource availability, ecological functioning, natural hazard risk, and sea-level rise. These impacts highlight the importance of glacier reconstructions, which can improve predictions of glacier responses to future climate change (4) and generate valuable terrestrial paleoclimate data (5). In many mountainous regions of the Northern Hemisphere, however, glacier reconstructions spanning the Holocene are sparse, and those that do exist are often discontinuous and/or limited to periods of moraine construction (6). This shortage of data is particularly true in the western United States, where glacier systems achieved their maximum Holocene extents during the Little Ice Age (LIA; 1250 to 1900 CE) and landscape evidence for earlier Neoglacial advances is largely obscured (7, 8).

Moraine sequences in the western United States typically mark the timing and positions of alpine glaciers during deglaciation from their Last Glacial Maximum (Pinedale age) positions and, further up-valley, during their late Holocene LIA maxima (8-10). Thus, very little is known about the history of glacier systems between their latest Pleistocene retreat and latest Holocene culmination, including whether alpine glaciers completely disappeared during the warmth of the early Holocene and the timing of reformation or readvance during Neoglaciation (11). An incomplete glacial record precludes our ability to place modern changes in a greater context and hinders our understanding of how alpine glaciers respond to variable climate over centennial to millennial time scales. Lake basins situated proximal to ice limits yet outside the zone of disturbance offer a solution to this problem, because their sediments contain continuous Copyright © 2020 The Authors, some rights reserved; exclusive licensee American Association for the Advancement of Science. No claim to original U.S. Government Works. Distributed under a Creative Commons Attribution NonCommercial License 4.0 (CC BY-NC).

records of past glacier activity (12, 13). Here, we target sediments from glacial and nonglacial alpine lake basins in the Teton Range, Grand Teton National Park (GTNP), Wyoming, to construct a continuous Holocene record of glacier fluctuations and attendant local climate changes.

#### **Alpine glaciers in the Teton Range**

During the Pinedale glaciation, the Teton Range was encompassed by the Greater Yellowstone Glacial System, which represented one of the largest ice masses in the western United States outside of the Laurentide and Cordilleran ice sheets (Fig. 1) (14, 15). The terminal positions of Teton glaciers during the Pinedale are marked by a series of prominent moraines impounding range-front lakes (see the Supplementary Materials). Previous work characterizing and dating these features (primarily using cosmogenic <sup>10</sup>Be dating of moraine boulders and radiocarbon dating of macrofossils contained in lake sediments) documents deglaciation as initiating by ~15 thousand years (ka) and finishing by ~11.5 ka (15–17). This timeline is broadly similar to that documented in mountain ranges throughout the western United States (8, 10).

Contemporary glaciers in the Teton Range, as in other western U.S. ranges, are positioned in up-valley cirques and are, in most cases, retreating from end moraines constructed during the LIA. There are presently 10 named glaciers and numerous additional unnamed glaciers and rock glaciers occupying high-elevation catchments in GTNP, often in shaded northerly or north-easterly aspects. These features provide important ecosystem services and have attracted scientific interest for decades (18). Teton Glacier is the largest and most prominent glacier in the Range, occupying a deep cirque below the sheer north and east faces of the two highest Teton peaks (Fig. 1). Winter mass balance measurements indicate that Teton Glacier is sustained by anomalously high seasonal accumulation due to abundant orographic snowfall and snow redistribution (primarily by wind and avalanching) (19). Anecdotal observations made in the 1920 CE document only modest retreat from its large, sharpcrested end moraine, suggesting that maximum LIA dimensions

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**Fig. 1. Teton Range study area and regional context.** Oblique aerial view of study site showing the geomorphic setting of the glacier-fed Delta Lake below Teton and Dike Glaciers and nearby nonglacial Surprise Lake. Inset map of Pinedale glacier extents in the western United States (14) and location of Teton Range (yellow star), Holocene glacier records [blue triangles: Conness Glacier (CG), Palisade Glacier (PG), Glacier National Park (GNP), Mt. Baker (MB), and Mt. Rainier (MR)], and hydroclimate reconstructions [red circles: Rocky Mountain lake level records (4d), Bison Lake  $\delta^{18}$ O (4e), and winter precipitation records (4f)] mentioned in text and shown in Fig. 4). (Image credit: Google Earth based on Landsat/Copernicus data).

were attained in the decades prior (18). The disproportionately large size of this moraine and substantial surface debris cover near the glacier terminus are testament to frequent rockfall from the surrounding cirque walls. Glaciological studies have shown that Teton Glacier and others in the central Tetons fluctuated in area and volume in response to 20th century climate variability (20) and predict their ongoing retreat to persist over the next century as anthropogenic warming continues (21). These concerns and the importance of these glacial features for ecosystems in the National Parks have prompted resource managers at GTNP and other National Parks in the western United States to initiate coordinated efforts to survey and monitor their disappearing glacier resources (22). Continuous and precisely dated Holocene records are prerequisite for interpreting modern observations within a long-term context.

#### RESULTS

#### Lake basins and sediment stratigraphy

To develop a continuous record of glacier fluctuations in the Tetons and local Holocene climate changes, we analyzed physical and geochemical proxies in sediment cores from two small, high-elevation lakes: Delta Lake [2755 meters above sea level (masl); 0.03 km<sup>2</sup>; max depth, ~8.0 m], a glacial tarn positioned roughly 1 km below the Teton Glacier terminus, and Surprise Lake (2920 masl; 0.01 km<sup>2</sup>; max depth, ~7 m), a nearby nonglacial lake in an adjacent watershed (see Materials and Methods and Fig. 1). The proximity and similar morphometry of the two basins, combined with contrasting sediment transport systems (i.e., glacial versus nonglacial), make them complementary recorders of glacier activity and climate variability, respectively. Approximately 20% of Delta Lake's catchment is occupied by glacier ice of the Teton (~2.2 km<sup>2</sup>) and Dike (informal name;  $\sim 0.7$  km<sup>2</sup>) glaciers, which, through meltwater and glacier erosional processes, dominate lake inflow and sediment flux. High sediment production and delivery from these sources are evident in the prominent inflow delta and the high load of glacier flour suspended in the lake water column. Surprise Lake is situated in a minor cirque below neighboring Amphitheater Lake, which provides overflow via a short inlet stream and also acts as a sediment trap for material sourced from the steep slopes of the upper catchment (Fig. 1). High snowfall accumulation results in prolonged seasonal lake ice cover, which can commonly persist for 9 months, and snowmelt is the primary inflow source to these nonglacial lakes. Surprise Lake drains to the south over a bedrock lip, but during dry years, lake water level can fall below its outlet (see the Supplementary Materials).

We sampled the sediment fill preserved in Delta and Surprise Lakes at multiple locations using a lance-driven piston corer deployed from the lake surfaces (see Materials and Methods). Sediment cores were split, imaged, and analyzed for glacier and climate indicators using conventional methods (see Materials and Methods; fig. S1 and table S1). A composite stratigraphic sequence was developed for each lake and age control established using accelerator mass spectrometry radiocarbon dating and the position of the 7.6-ka Mazama tephra layer (see Materials and Methods; Fig. 2 and table S2). We focus our analyses on the past ~10 ka common to both lake sequences. During this interval, the average length of time between age control points is ~1300 years.

The composite core from Delta Lake is 10.6 m long and contains minerogenic glacial-lacustrine sediments, characterized by relatively high density, low organic matter (OM) content, and rapid sediment accumulation (Fig. 2 and table S1). Core stratigraphy consists of alternating light gray to dark gray siliciclastic fine sand, silt, and clay, with faint and indistinct banding near the core bottom that transitions to well-defined rhythmic laminations toward the top (Fig. 2 and fig. S1). Average density values and OM concentrations are  $1.2 \pm 0.2$  g cm<sup>-1</sup> and  $3.3 \pm 1.3\%$  (range, 0.7 to 1.8 g cm<sup>-1</sup> and 1.1 to 9.7%), respectively, and reveal a pattern of increasing density and decreasing organic content through time that tracks changes in lithostratigraphy. Sediment accumulation rates increase from approximately 60 cm ka<sup>-1</sup> in the early Holocene to >200 cm ka<sup>-1</sup> during the past few centuries. In contrast, the composite core from Surprise Lake is 3.0 m long and contains mostly homogenous organic-rich, low-density sediments with relatively slow accumulation rates that range from 15 to 60 cm  $ka^{-1}$  (fig. S1 and table S1). Density and OM values are  $0.3 \pm 0.07$  g cm<sup>-1</sup> and  $16.9 \pm 2.3\%$  (range, 0.2 to 0.6 g cm<sup>-1</sup> and 11.3 to 27.0%), respectively, and remain generally consistent through the duration of the record.

#### Sedimentary signals of glacier and environmental change

The Holocene stratigraphy and sediment lithology of the two lakes highlight differences in their sedimentation regimes (Fig. 2). Sediment production and delivery to Delta Lake are controlled by subglacial erosion and meltwater discharge from upstream glaciers. We interpret both processes to vary as a function of glacier size, such that changes in the physical nature of Delta Lake sediments on multidecadal and longer time scales reflect changes in glacier mass



Fig. 2. Lake sediment lithostratigraphy and sedimentology. Stratigraphic logs of Delta and Surprise Lake sediment cores showing positions of radiocarbon and tephra age control depths and sedimentary parameters: sediment accumulation rate (SAR), dry bulk density (Density), and organic matter (OM) concentration.

balance associated with the evolution of regional climate (13). In comparison, the character of Surprise Lake sediments indicates that the lake has remained free from glacial influence for at least the past 10 ka, and its position downstream of a sediment trap in Amphitheater Lake has reduced the influx of clastic material and other debris from hillslope processes. We therefore interpret changes in Surprise Lake sediment parameters to reflect changes in local environmental conditions related to climate and lake hydrology.

Variations in Teton glacier activity are tracked through a combination of three independent but complementary methods for quantifying changes in glacial-lacustrine sediment: silt and clay flux (SC<sub>O</sub>; measured via particle size analyzer), clastic mineral flux (Clastic<sub>o</sub>; defined as the nonorganic component as determined by loss on ignition), and principal components analyses (PCAs) of elemental abundances [PC2 of all x-ray fluorescence (XRF)-measured elements] (see Materials and Methods). The influx of all three glacial indicators shows similar patterns in glacier activity over the past 10 ka (Fig. 3). Low and constant meltwater influx from 10 to ~6.3 ka is followed by a long-term, gradual rise and stepwise increase at ~3.9 ka. Subsequent maxima in all parameters occur at ~2.8 and 0.1 ka (Fig. 3). The two intervals of increased glacial sedimentation are separated by a distinct relative minimum between 2.4 and 0.7 ka. This relative minimum in sediment flux at Delta Lake corresponds temporally with a prominent peak in OM flux (determined via loss on ignition) and diatom productivity [biogenic silica (BSi) measured via Fourier transform infrared spectroscopy (FTIRS)] at Surprise Lake, which otherwise maintains stable values during the Holocene (see Materials and Methods; Fig. 3).

#### DISCUSSION

#### **Holocene glacier fluctuations**

Consistently low sediment flux and reduced meltwater from Teton Glacier between 10 and 6.3 ka coincide with mild conditions and increased primary productivity at nearby Jenny Lake (16) and occur



Fig. 3. Teton Glacier and local climate reconstructions. Glacier indicators measured in Delta Lake sediments (blue): (A) PC2 of scanning XRF elemental data, (B) clastic mineral flux, and (C) influx of silt and clay size grains (Silt + clay flux). OM productivity indicators measured in Surprise Lake sediments (red): (D) OM flux and (E) diatom productivity inferred from biogenic silica (BSi) flux (FTIRS absorbance units). Heavy black line is locally estimated scatterplot smoothing (LOESS) function for each panel. Blue shade bars indicate phases of Neoglacial advance.

when other sites in the Rocky Mountains reflect considerably more aridity (23-25) and/or warmer summers than present (Fig. 4) (26, 27). These conditions are consistent with high summer insolation in the early Holocene that resulted in maximum summer temperatures and the major reduction or complete disappearance of alpine glaciers throughout the western United States (9). The stable but distinctly glacial character of Delta Lake sediments suggests that glacial ice persisted continuously in some form through the early Holocene, either as a much-reduced debris-covered glacier or as a rock glacier. In a warming climate, debris-covered glaciers are expected to transition to rock glaciers, which can persist even when the equilibrium line altitude is above local topography given sufficient debris flux and redistributed snow (28)-conditions typified in the modern Teton Glacier cirque (19). We therefore suggest that Teton Glacier was a glacier-derived rock glacier during the warmth and aridity of the early Holocene and was minimally erosive and mostly unresponsive to regional climate until ~6.3 ka.

An increase in minerogenic sediment delivery beginning ~6.3 ka marks a transition from glacier dormancy to activation and ice growth during Neoglaciation (Fig. 3). We note that this transition is expressed as a gradual but unidirectional shift in lake sediment lithology, indicative of a shift from rock glacier to debris-covered glacier, rather than a sharp threshold-type signal observed in many Holocene



**Fig. 4. Ten-ka glacier and climate records from the Rocky Mountains.** (**A**) 45°N June insolation (*54*); (**B**) Jenny Lake total organic carbon (TOC) flux (*16*); (**C**) Jenny Lake BSi flux (*16*); (**D**) median lake level (with ±1 SD as gray error envelope) reconstructed from five lakes in Wyoming and Colorado (table S3) (*25*); (**E**) sediment carbonate oxygen isotope ( $\delta^{18}$ O) (per mil, ‰) record from Bison Lake, Colorado, as a proxy for variations in the seasonality of precipitation (*37*); (**F**) winter precipitation anomaly reconstructed from six high-elevation lakes in the Park Range, northerm Colorado (*44*); and (**G**) glacier-derived clastic sediment flux at Delta Lake (this study). Heavy black lines are LOESS functions in (B), (C), (E), (F), and (G). See Fig. 1 and table S3 for locations of regional lake sediment records. Blue shade bars indicate phases of Neoglacial advance.

glacial-lacustrine records where glaciers completely disappeared from lake catchments during early Holocene warmth (29). The onset of this advance coincides with the well-documented Garibaldi glacial phase in the Coast Mountains and Canadian Rockies (30) and with more sparse evidence for ice growth in the western United States, where glaciers expanded on Mt. Baker, Washington (31), and reappeared in Glacier National Park, Montana, for the first time following their disappearance in the early Holocene (Fig. 1) (32).

The start of two millennial-scale phases of Teton Glacier advance in the late Holocene is signified by an increase in sediment flux at 3.9 ka (Fig. 3). The first phase is expressed as a ramp up in all glacier proxies that culminates between 3.2 and 2.4 ka. Like the mid-Holocene expansion, the timing of this advance overlaps with glacier advances in western Canada (*30*) and the western United States, including glacier expansions at Glacier National Park (*32*) and Mt. Rainer, Washington (*33*), and the onset of Neoglacial advances at Conness Glacier and Palisade Glacier in the Sierra Nevada, California (Fig. 1) (*34*, *35*). The second and most extensive phase of ice growth culminates between 0.7 and 0.1 ka and defines the local expression of the LIA (Fig. 3). Peak clastic sedimentation and meltwater influx at ~0.1 ka are aligned with visual observations of Teton Glacier retreating from near its LIA limit (18) and is broadly synchronous with maximum glacier configurations throughout the western United States (7).

#### **Climate controls on Teton Glacier fluctuations**

The coherent structure of Neoglacial advances in the Tetons and their agreement with ice growth in other mountain ranges imply regionally consistent glacier responses to millennial-scale changes in climate over western North America. Early Neoglacial advances at ~6.3 ka are temporally consistent with a distinct hemispheric-scale multicentennial cold event involving reorganization of ocean and atmospheric circulation that has been associated with decreased solar irradiance (36). However, the persistent nature of glacier expansion in the Tetons suggests that while a relatively short-duration cold event may have triggered an initial advance, long-term ice growth must have been sustained by a more continuous forcing mechanism, such as the monotonic decline in summer insolation and/or a shift to greater winter precipitation, for example, due to changes in moisture delivery associated with the evolution of the El Nino-Southern Oscillation (37, 38) or the latitudinal temperature gradient (39). A strong shift toward greater moisture balance after ~6 ka is demonstrated by rising water levels in lakes throughout the central and southern Rocky Mountains (Fig. 4D) (25).

Declining summer insolation punctuated by global cooling events and combined with increasingly wetter conditions all support progressive glacier expansion. However, the distinct two-phase Neoglacial advance shown here is not predicted by these forcings alone, nor is this pattern commonly observed in Holocene glacier reconstructions from the western United States. Most notably, the prominent retreat of Teton Glacier ~2.4 to 1.0 ka reflects an extended period of local climate conditions that promoted negative glacier mass balance, which nominally contradicts evidence for a global cold event (36) and glacier advances elsewhere in the western United States (31, 32, 35). We hypothesize that this contrasting glacier behavior during the late Holocene can be explained, in part, by spatial heterogeneity of hydroclimate in mountainous regions of the western United States.

To assess the local climate state responsible for glacier behavior over centennial time scales, and in particular the late-Holocene retreat, we turn to the sediment record in Surprise Lake. Environmental parameters in Surprise Lake are stable through the Holocene except for one interval of exceptionally high diatom production and OM flux that coincides directly with the phase of Teton glacier retreat (Fig. 3). Recent primary productivity in high-elevation lakes in the Tetons and elsewhere in the western United States has been affected by modern climate change and nutrient loading (40, 41). In particular, it has been demonstrated that winter snowpack is the most important factor in determining lake productivity in a small alpine lake in the Sierra Nevada, California, by regulating the timing and rate of snowmelt, which controls seasonal light availability, growing season length, nutrient availability, and water temperature (42). Accordingly, lake productivity and algal biomass are greater during dry years. At Surprise Lake, the influence of snowpack variability is exaggerated due to its unique hydrological setting, where low snowpack results in restricted inflow, low lake water levels, and hydrologic closure of the basin (see the Supplementary Materials). We therefore interpret the greatly increased productivity ~2.4 to 1.0 ka

to be a consequence of sustained reductions in snowpack due to low winter precipitation in the Tetons (Fig. 3).

The pronounced interval of Teton Glacier retreat corresponds to dry conditions registered at Surprise Lake and other sites across the central and southern Rockies. For example, multiproxy data from Crevice Lake in northern Yellowstone National Park suggest a period of extreme drought between 2.2 and 0.8 ka (43), and a trend of reduced snowfall from 2.4 to 1.0 ka followed by increased snowfall during the past millennium is indicated by a quantitative reconstruction of winter precipitation from a series of small high-elevation lakes in the Park Range, northern Colorado (Fig. 4F) (44). This pattern is also supported by stratigraphic evidence for the timing of Holocene highstands beginning after 1.0 ka in similar high-elevation lakes in the area (Fig. 4D) (25), as well as shifts in temperature, atmospheric circulation, and/or snowfall-dominated precipitation at Bison Lake in the Colorado Rockies (Fig. 4E) (37, 45). Moreover, the timing of reduced moisture in the central/southern Rockies overlaps with the so-called Late Holocene Dry Period identified in multiple paleorecords across the Great Basin (46). Combined, the Surprise Lake proxy data and other independent hydroclimate reconstructions point toward a prolonged episode of reduced winter precipitation that led to a diminished snowpack in the Tetons, resulting in net glacier retreat for over a millennium between Neoglacial advances (2.4 to 0.7 ka). These results underscore the sensitivity of alpine glaciers to changes in winter precipitation patterns and demonstrate the ability of glacier reconstructions to capture changes in local climate well outside the range of modern variability.

#### **Glacier resilience and future projections**

The continuous 10-ka record presented here reveals glacier fluctuations over centennial, and longer time scales in the Tetons were driven by low-frequency local precipitation changes superposed on long-term regional cooling trends. In the future, glaciers are likely to retreat as summer temperatures continue to rise, but changes in winter snowfall are more difficult to predict and could play an important role in the details of glacier variability over various time scales as precipitation patterns vary (47). At present, Teton Glacier is sustained by high orographic precipitation and added inputs from wind reworking and avalanching. The Delta Lake record indicates that glacier ice survived for millennia, possibly as a stagnant rock glacier insulated by debris cover, during conditions in the early Holocene that were warmer and/or drier than present (28). On the basis of this record, we suggest that some glaciers in the western United States may transition to rock glaciers and thus continue to provide some ecosystem and geomorphic functions into the future despite unfavorable climate projections.

#### **MATERIALS AND METHODS**

#### Sediment coring and chronologies

Sediment cores were collected from multiple locations in Delta and Surprise Lakes in an overlapped manner through repeated drives using Livingston-type and Bolivia-type, lance-driven piston corers (table S1). Delta Lake was cored in winter from the frozen lake surface; Surprise Lake was cored in summer from a pontoon raft. Core sections were packaged in the field and transported to the National Lacustrine Core Facility (LacCore) at the University of Minnesota and the Scripps Institute of Oceanography, University of California, San Diego, for initial core processing. Core sections were split lengthwise into working and archival halves, and core halves were photographed using a linescan core imager (fig. S1).

Age control of lake sediments was established using radiocarbon dating of terrestrial macrofossils and tephrochronology (table S2). Terrestrial plant remains (e.g., conifer needles, charcoal, and woody plant fragments) were relatively abundant in both Delta and Surprise Lake sediment sequences. Samples selected for radiocarbon dating were pretreated at the University of Pittsburgh and the University of Colorado and measured at the W.M. Keck Carbon Cycle Accelerated Mass Spectrometry Laboratory, University of California, Irvine. Radiocarbon results were calibrated and converted to calendar years before present using CALIB 7.0 with the IntCal13 calibration curve (48, 49). The radiocarbon chronologies for both lakes are bolstered by the position of the Mazama ash bed (~7.6 ka) (50), which has been previously characterized in Teton lake sediments (16). Age-depth models for all lake cores were constructed using a smooth spline interpolation of individual control points and the classical age modeling code for R software (fig. S2) (51).

#### **Sedimentary analyses**

To reconstruct glacier and environmental changes, we measured sediment accumulation rate, bulk density, OM content, clastic sediment concentration, grain size distribution, and elemental abundance. Raw values were converted to fluxes using bulk density values and calculated sediment accumulation rates. Sediment dry bulk density was measured at continuous 2-cm intervals by weighing 1-cm<sup>3</sup> samples after drying in a low-temperature oven (~60°C). Total organic content was measured at 2-cm intervals using loss on ignition at 550°C for 4 hours. Grain size distributions were measured on cores from Delta Lake at 5-cm intervals using a Malvern Mastersizer 3000 laser particle size analyzer at the California State University at Fullerton. The elemental composition of Delta Lake sediments was determined at 5-mm resolution by scanning XRF (sXRF) using an Avaatech core scanner at the Scripps Institute of Oceanography, University of California, San Diego, operated using an exposure time of 10 s, a voltage of 10 kV, and a current of 500 mA. BSi, a proxy for lake diatom abundance, was inferred for Surprise Lake sediments via FTIRS (52). Samples for FTIRS analyses were taken at 2-cm intervals, dried, and homogenized with potassium bromide in a 1:50 dilution. We analyzed each sample three times using an FTIR Research Spectrometer Vertex 70v with the Praying Mantis Attachment using advanced measurements with a resolution of 2 cm<sup>-1</sup> (52). The samples were analyzed using OPUS software and results averaged. We report BSi in absorbance units (uncalibrated to % BSi) and thus only interpret relative changes downcore. Glacial meltwater is characterized by its high clastic load and abundance of suspended glacial flour (silt and clay sized grains) (12). To capture the mineralogical fingerprint of glaciogenic sediment, we performed PCA on all sXRF-generated elemental abundance data. PCA was conducted using the PCA function within the R package FactoMineR (53) with all default settings. PCA results are summarized in fig. S4. The first component (PC1) explains 43.7% of the variance but shows little coherent relationship with sediment age. Rather, PC1 captures highfrequency lithologic changes, which appear to be associated with changes in fine-scale laminae thickness due to seasonal changes in grain size deposition at Delta Lake through the record. PC2 explains 17.3% of the variance and systematically increases through time, likely capturing millennial-scale changes in glaciogenic sediment flux. We thus present PC2 as a proxy for glacier size in Fig. 3A.

#### SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/6/47/eabc7661/DC1

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