KECK GEOLOGY CONSORTIUM

PROCEEDINGS OF THE TWENTY-FOURTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

April 2011
Union College, Schenectady, NY

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ISSN# 1528-7491

The Consortium Colleges The National Science Foundation ExxonMobil Corporation

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2010-2011 PROJECTS

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Students: *JESSE DAVENPORT*, College of Wooster, *KRISTINA DOYLE*, Amherst College, *B. PARKER HAYNES*, University of North Carolina - Chapel Hill, *DANIELLE LERNER*, Mount Holyoke College, *CALEB O. LUCY*, Williams College, *ALIANORA WALKER*, Smith College.

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Students: *ERIN CAMP*, Amherst College, *EVAN N. DETHIER*, Williams College, *HAYLEY CORSON-RIKERT*, Wesleyan University, *KEITH M. KANTACK*, Williams College, *ELLEN M. MALEY*, Smith College, *JAMES A. MCCARTHY*, Williams College, *COREY SHIRCLIFF*, Beloit College, *KATHLEEN WARRELL*, Georgia Tech University, *CIANNA E. WYSHNYSZKY*, Amherst College.

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Students: *HANNAH BOURNE*, Wesleyan University, *JONATHAN GRIFFITH*, Union College, *JACQUELINE KUTVIRT*, Macalester College, *EMMA LOCATELLI*, Macalester College, *SARAH MATTESON*, Bryn Mawr College, *PERRY ODDO*, Franklin and Marshall College, *CLARK BRUNSON SIMCOE*, Washington and Lee University.

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Students: *BRIANA BERKOWITZ*, Beloit College, *DAENA CHARLES*, Union College, *MELLISSA CROSS*, Colgate University, *JOHN MICHAELS*, North Carolina State University, *ERDENEBAYAR TSAGAANNARAN*, Mongolian University of Science and Technology, *BATTOGTOH DAMDINSUREN*, Mongolian University of Science and Technology, *DANIEL ROTHBERG*, Colorado College, *ESUGEI GANBOLD*, *ARANZAL ERDENE*, Mongolian University of Science and Technology, *AFSHAN SHAIKH*, Georgia Institute of Technology, *KRISTIN TADDEI*, Franklin and Marshall College, *GABRIELLE VANCE*, Whitman College, *ANDREW ZUZA*, Cornell University.

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Students: *SHANNON BRADY*, Union College. *LOGAN SCHUMACHER*, Pomona College, *HANNAH ZELLNER*, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION

Faculty: *JADE STAR LACKEY*, Pomona College, *STACI L. LOEWY*, California State University-Bakersfield
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EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSAROKA RANGES, WYOMING

Faculty: *JOHN CRADDOCK*, Macalester College, *DAVE MALONE*, Illinois State University
Students: *JESSE GEARY*, Macalester College, *KATHERINE KRAVITZ*, Smith College, *RAY MCGAUGHEY*, Carleton College.

Funding Provided by:
Keck Geology Consortium Member Institutions
The National Science Foundation Grant NSF-REU 1005122
ExxonMobil Corporation

Keck Geology Consortium: Projects 2010-2011
Short Contributions— Glacier National Park

GEOMORPHIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA, U.S.A.
Project Faculty: KELLY MACGREGOR, Macalester College, CATHERINE RIIHIMAKI, Drew University, AMY MYRBO, KRISTINA BRADY LacCore Lab, University of Minnesota

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A CONTINUOUS LATE HOLOCENE RECORD OF PALEOCLIMATE CHANGE FROM GRINNELL LAKE SEDIMENT CORES, GLACIER NATIONAL PARK, MONTANA

JONATHAN GRIFFITH, Union College
Research Advisor: Donald Rodbell

INTRODUCTION

Glaciers are sensitive to climate change, waxing and waning in response to changes in temperature and precipitation. Glacial fluctuations recorded in sedimentary deposits are likely to preserve information about the past climatic history (Benn and Evans, 1998). In particular, the high sensitivity of alpine glaciers to climate change makes records of their fluctuations among the best proxies for reconstructing climate variability (Licciardi, 2004). However, the relationship between alpine glaciers and climate is complex because alpine glaciers fluctuate in response to changes in both temperature and precipitation, and their response is frequently lagged in time (Luckman, 2000).

Our understanding of Holocene glaciations in the Rocky Mountains of North America has been largely based on the discontinuous moraine record (Leonard, 1986). However, recent studies have interpreted variations in glacial extent from proglacial lake sediments suggesting that lake sediments might be used as indicators of upvalley glacial activity. Therefore, lake sediments provide continuous records of glaciations, recording advances, retreats, and maximum ice extents (Rosenbaum and Reynolds, 2004). Interpreting downvalley lacustrine sediments is difficult because of a lack of understanding of the relationship between glacial activity and downvalley sedimentation. Glacial sediments can at times be sequestered subglacially and at other times be flushed from storage by high runoff events (Rosenbaum and Reynolds, 2004). Despite potential issues reconstructing glacial records based on downvalley sedimentation rates, Leonard (1985) concluded that glacially-derived sediments from Hector Lake, Alberta largely reflect the extent of alpine glaciation when averaged over timescales of decades to centuries with periods of increased ice extent corresponding to high sedimentation rates. Other studies suggest that there is an inverse relationship between clastic sedimentation rate and organic content of sediments (Karlen, 1981). Karlen (1981) interpreted changes in organic content as indicators for changes in upvalley glacier extent suggesting that an increase of glacial debris in the water column results in lower organic production. This study aims to document and interpret changes in clastic sediment flux and carbon content as indicators for glacial extent.

OBJECTIVES

The objective of this study is to reconstruct a recent climate history of Grinnell Lake, eastern Glacier National Park, Montana from geological evidence of glacier fluctuations preserved in a proglacial lake. To accomplish this goal, I will examine a ~1,200 year-long sediment core from Grinnell Lake to determine the relationship between climate, glacial activity, and the subsequent development, transport, and deposition of clastic and organic material.

STUDY SITE

Grinnell Lake, located east of the Continental Divide, is one of four lakes in the Grinnell Glacier/Many Glacier valley and has a catchment area of about 25 km2 that includes the Grinnell Glacier (~2000 m elevation) (MacGregor et al., 2011). The lakes include Upper Grinnell Lake, Grinnell Lake (study site; Fig. 1 of the project summary), Lake Josephine, and Swiftcurrent Lake (listed in order from upvalley to downvalley.

The Grinnell Lake drainage basin is underlain by sedimentary rocks of the Middle Proterozoic Belt Supergroup ranging from about 1,600 Ma to 800 Ma (Carrara, 1989). The Supergroup consists of largely argillaceous, arenaceous, and calcareous strata. Grinnell

Glacier is currently eroding the stromatolitic Siyeh Limestone of the Helena Formation, the only source of dolomite in the valley (MacGregor et al., 2011). The Grinnell Glacier valley is characterized by steep hillslopes; between Mount Grinnell and Grinnell Lake (~2 km distance) there is a 1 km change in elevation (MacGregor et al., 2011). The Grinnell Glacier is bordered by a ~500-m-high headwall. A 460 m step in topography exists between Upper Grinnell Lake and Grinnell Lake over which water from Upper Grinnell Lake flows (MacGregor et al., 2011).

Since the Grinnell Glacier was first observed in 1887, it has receded at a rate of about 6 m a-1. From 1920 to 1946 the Grinnell Glacier experienced the largest retreat of any glacier in Glacier National Park with an average recession rate of 15 m a-1 (Key et al., 2009). The retreat of glaciers observed in Glacier National Parks is consistent with trends in temperate glaciers in other regions over the last 150 years (Key et al., 2009).

Figure 1. Sediment within the white box from cores 1C-2B-1 (left) and 1B-1P-1 (middle) was used to get the continuous 1.17 cm sediment core (right) that was analyzed.

METHODS

Overlapping cores LGRIN10-1B-1P-1 and LGRIN10-1C-2B-1 were collected in July 2010 using a modified Livingstone-type piston corer (Wright, 1967). The cores were logged for magnetic susceptibility and bulk density, split, digitally photographed, and described using smear slides at LacCore, University of Minnesota. Correlative units were identified in each core from photographs and used to construct a single 1.17-m-long core consisting of a 0.75 m surface core (LGRIN-1B-1P-1) and an additional 0.42-m-long core (LGRIN-1C-2B-1) (Fig. 1). This single core was then subsampled at 0.5-cm spacing until a depth of 50 cm and at 1-cm intervals thereafter. Samples were then mailed to Union College where analytical measurements including carbon coulometry, and biogenic silica extraction were conducted.

Analysis of total carbon (TC) was conducted using a CM 5200 Autosampler Furnace. Samples for TC were combusted in oxygen at 1000°C to convert organic and inorganic forms of carbon to CO2. The CO2 released was measured with a UIC coulometer. Analysis of total inorganic carbon (TIC) was conducted using a CM 5230 TIC, the same sampling procedures followed for TC analyses were applied to the TIC analyses. Inorganic carbon was determined by measuring the CO2 released after the samples were acidified in 2N HClO4. Total organic carbon was determined by subtracting TIC from TC: TOC=TC-TIC.

Silica components in lake sediment (primarily diatoms, sponge spicules, and silicate minerals) can be separated (Conley and Schelske, 1992) by dissolving samples in a strong basic solution because dissolution rates vary between siliceous components. Twenty-four samples, collected longitudinally every 5 cm from the sediment cores, were analyzed for biogenic silica (bSi) following the extraction technique outlined in DeMaster (1981). Details of analytical procedures are available at: <http://www1.uni-on.edu/~rodbelld/CoreLab.html>. Samples were analyzed for dissolved silica (DSi) by Inductively-Coupled-Plasma Mass Spectroscopy (ICPMS). Weight percent bSi is determined by regression analysis on the increase of DSi concentration with time and then extrapolation back to the y-intercept to determine the bSi in the sediment sample (Conley and Schelske, 1992). The y-intercept represents the weight percent bSi relative to the original sample mass. These data were used to calculate the flux of clastic sediment (Fluxclastic) from:

Fluxclastic = SR(BD - ((BD x TOM) + (BD x bSi))

Where SR is the linear sedimentation rate (cm yr-1), BD is the bulk density (g cm-3), TOM the weight fraction organic matter of the bulk sediment, and bSi is the weight percent of biogenic silica in the sample. TOM was calculated from TOC (%)/44 to reflect the molar ratio between plant cellulose (C6H10O5)n and TOC (%) (Rodbell et al., 2008).

To develop a chronology, terrestrial material was extracted from the core at cumulative depths of 65 cm (wood fragment) and 90 cm (organic matter) to be radiocarbon dated. The samples were dated at UC-Davis radiocarbon lab. Using CALIB 4.0, radiocarbon ages were converted to calibrated calendar years by calculating the probability distribution of the samples true age. The mean of this distribution was used in this study to approximate the calendar year. All calendar years are reported in "years before present" (B.P.), which, is the number of radiocarbon years before 1950. The sediment surface (0 cm) was assumed to represent the present, which, in this study was assumed to be 1950.

DATA AND INTERPRETATION

Two accelerator mass spectrometry (AMS) radiocarbon (14C) dates indicate that the 1.17 meter-long lacustrine sediment core extracted from Grinnell Lake provides an ~1200 cal yr B.P.-to present lake record. To account for the lack of dated material in the bottom of the core (below the oldest radiocarbon age of ~922 cal yr B.P. and depth of 96 cm), a linear approximation interpolation through the core was applied and used to estimate sedimentation rates, which were extrapolated below 96 cm (Fig. 2). Core depths were then converted to calendar years and used in the remaining text.

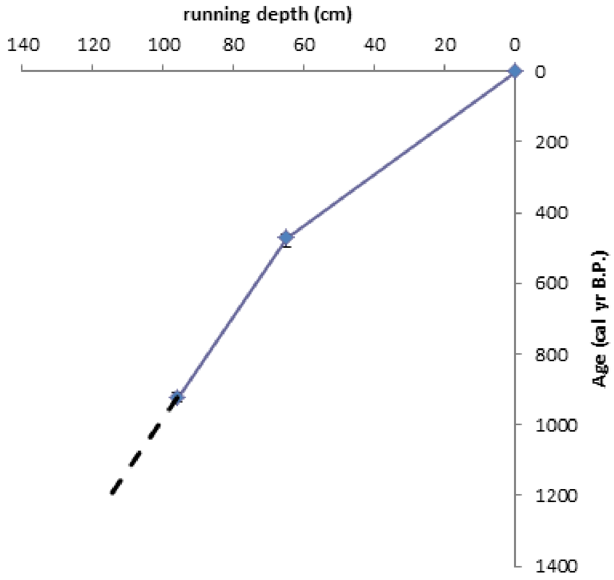

Figure 2. Age-depth model for Grinnell Lake derived from linear interpolation of AMS radiocarbon dates which were converted to calibrated calendar years (plotted in blue). The sedimentation rate from 0-470 cal yr B.P. was 0.138 cm/yr, while the sedimentation rate from 470-1200 cal yr B.P. was only 0.069 cm/yr.

CARBON CONTENT

Allochthonous or external source material enters lakes in various forms and is generally inversely related to organic carbon. Although lakes can be less productive during times of glacial advance, it is also important to note that autochthonous organic carbon may simply be diluted by the influx of clastic sediment in the record. All inorganic carbon deposited in Grinnell Lake was assumed to be allochthonous because the lake is fed by glacial meltwater and receives precipitation throughout the year making authigenic carbonate unlikely. Throughout the core set, peak inorganic carbon values are inversely related to organic carbon data. Percent inorganic carbon is nearly absent from the record for the first 300 years however a pronounced spike ~1090 denotes the deposition of allochthounous material (Fig. 3). Circa 1500, inorganic carbon values exceed 1.5% and coincide with the lowest % organic carbon values in the record. From ~1500-1870, pulses of inorganic carbon are present in

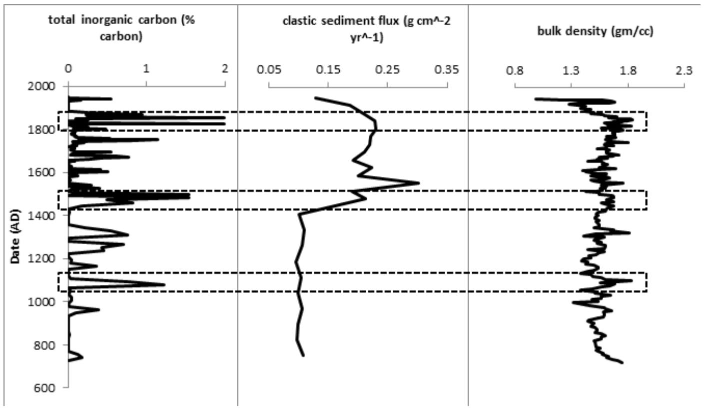

Figure 3. Plots of percent inorganic carbon, bulk density, and clastic sediment flux through time. Percent inorganic carbon, bulk density, and clastic sediment flux track together and reflect changes in the input of allochthonous material to Grinnell Lake. Boxes denote interpreted periods of glacial advances.

the record about every 90 years, with the pulses increasing in magnitude towards the surface. The greatest % inorganic carbon values exist in 1852 and 1856. The inorganic carbon peak ~1856 denotes the last significant pulse of inorganic carbon to the lake, and low inorganic carbon values persist until today.

BULK DENSITY & CLASTIC SEDIMENT FLUX

Bulk density profiles of sediment indicate hydrological changes within a lake basin, which are related to changes in ice extent (Cohen, 2003). Alpine glaciers occupying the headwaters of small, high-altitude valleys are the dominant hydrological control governing sedimentation in a lake basin (Cohen, 2003). Increased precipitation and decreased temperatures are two climatological parameters that increase ice volume, and thus the volume of meltwater able to transport sediment. Meltwater entrains dense sediment, such as glacial flour, thereby increasing the bulk density of the lacustrine sediment. Conversely, periods of reduced meltwater flow allow for biogenic processes to dominate a lake leading to the accumulation of less dense organic matter. Therefore, bulk density data should track with total inorganic carbon and vary inversely with total organic carbon.

Clastic sediment flux has also been used as a proxy for interpreting ice extent with high flux measurements corresponding to increased ice extent. Therefore, clastic sediment flux, bulk density, and total inorganic carbon should track together and reflect the input of allochthonous minerogenic material to the lake.

Bulk density and clastic sediment flux values remain relatively stable from 740-1090 and inorganic carbon is nearly absent from the record (Fig. 3). A rapid increase in inorganic carbon at ~1090 corresponds to increases in both clastic sediment flux and bulk density. Clastic sediment flux values more than double from 1400-1480 and coincide with distinct peaks in both bulk density and inorganic carbon (Fig.3). The highest clastic sediment flux value occurs ~1550. This increase coincides with a significant increase in bulk density but only a small increase in inorganic carbon. From 1500-1850, overall increases in bulk density, % inorganic carbon, and clastic flux are shown with each reaching their greatest values at ~1850 (Fig. 3). The sharp decline in these three proxies following the 1856 anomaly denotes the beginning of glacial recession which has continued for the past 150 years.

GLACIAL HISTORY BASED ON GRINNELL LAKE SEDIMENT CORE

Evidence from tree rings, reconstructed sea levels, and dated moraines document a warm interval termed the Medieval Warm Period which began as early as 800 AD (Cronin et al., 2004) and preceded the Little Ice Age. The time distinguishing the end of the Medieval Warm Period and the beginning of the Little Ice Age was likely asynchronous globally. Moraine evidence from the Canadian Rockies indicate the expansion of glacial ice about 1050-1150 AD (Leonard, 1986; Grove, 2001). However, temperatures derived from an oxygen isotope profile through a stalagmite in New Zealand suggest the Medieval Warm Period persisted until about 1400 (Wilson et al., 1979). This interpretation was supported by a 1100-year tree ring record from New Zealand and studies from lake Nino-Megata and San-no-Megata in northeastern Japan (Cook et al., 2002; Kazuyoshi et al, 2010).

Initiation of the Little Ice Age in Glacier National Park is thought to have commenced around 1400 and persisted until ~1900 (Key et al., 2002). Documented glacial advances in the Canadian Rockies ~1100 mark the beginning of the Little Ice Age in this region

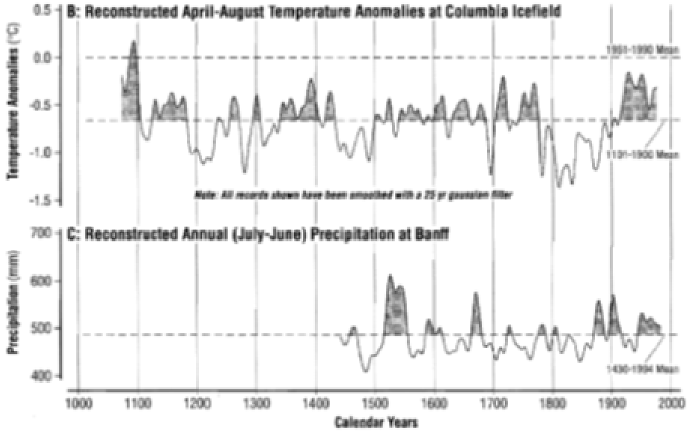

Figure 4. Comparison of reconstructed temperature (B) and precipitation (C) anomalies derived from tree rings in the Canadian Rockies. Maximum glacial extent occurred at the end of the 19th century (Figure 10 from Luckman, 2000).

(Grove, 2001). Initiation of the Little Ice Age in Glacier National Park is thought to have commenced ~1400 and persisted until ~1900 (Key et al., 2002). Documented glacial advances in the Canadian Rockies at ~1100 mark the beginning of the Little Ice Age in this region (Grove, 2001). Large pulses of inorganic carbon in the Grinnell Lake record at ~1090 and ~1480 each reflect the input of allochthonous material and represent possible periods of glacial expansion. Tree ring records from the Columbia Ice Field record anomalously low temperatures ~1200, ~1430-1500, and ~1800-1900 (Fig. 4) (Luckman, 2000). These periods of reduced summer temperatures correspond to the three most significant increases of inorganic carbon in the Grinnell Lake record. Therefore, I suggest that the initiation of the Little Ice Age in Glacier National Park began ~1100, earlier than has been previously documented.

The Little Ice Age does not display a continuous period of cooling or glacial conditions. Colder conditions are variable over the past thousand years, and are punctuated by intermittent periods of warmth (Leonard, 1986; Bradley and Jones, 1993). Therefore, the apparent decrease in the inorganic carbon record from ~1110-1430 might represent a warm period within the Little Ice Age and represent a period of little or no glacial expansion. The rapid increase in clastic sediment flux and inorganic carbon at ~1430 represents a return to a cool climate and glacial conditions. Clastic sediment flux, bulk density, and inorganic carbon all display increasing trends from ~1500-1850 and likely represent glacial readvances. Peak inorganic carbon and bulk density values coincident with high clastic sediment flux data ~1850 and reflect the period of maximum glacial extent when most moraines (>80%) were deposited (Carrara, 1989). Older moraines likely were destroyed during the mid-1800s advance. This interpretation is also supported by Leonard (1986) who determined that periods of glacial advance and/ or of cold temperatures of a century or more duration are reflected in periods of persistently high downvalley sedimentation. Leonard (1986) found sedimentation rates were highest in glacially-fed Hector Lake, Alberta ~1850 (Fig. 5).

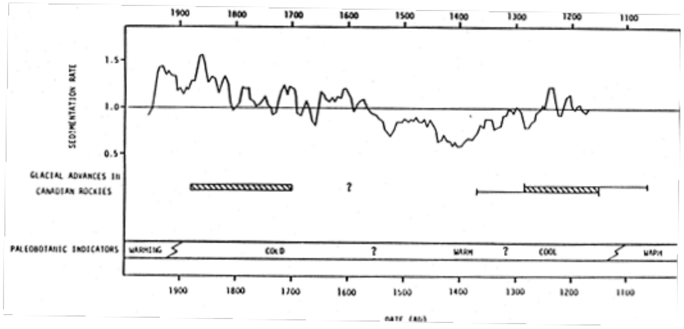

Figure 5. Composite sedimentation rate curve for glacial-fed Hector Lake, Alberta, Canada (~365 km northwest of the study site) compared with glacial history and paleobotanic indicators of climate in the Canadian Rockies over the past 900 years. Periods of increased sedimentation rates coincide with both Late Holocene glacial advances and occur during cool climates (Figure from Leonard, 1986).

Rapid decreases in % inorganic carbon, bulk density, and clastic flux from 1850 to the present mark the end of the Little Ice Age and the beginning of rapid glacial retreat in response to a warming climate. Changes in the Grinnell Glacier's position have been photographed and mapped since 1887 and document its rapid retreat and thus validate the usefulness of the proxy indicators listed above as tools for interpreting glacial histories.

CONCLUSION

A 1.2 kyr lacustrine sediment record extracted from Grinnell Lake in the northern Rocky Mountains of the United States provides a multi-proxy climate and glacial record in the Late Holocene. Glacial-interglacial fluctuations were documented and correlated with previously constructed records in regional geographical locations demonstrating the usefulness of clastic sediment flux to alpine lakes as a proxy indicator for the extent of regional ice cover (Rodbell et al., 2008; Leonard, 1986). Changes in clastic sediment flux are coincident with changes in percent inorganic carbon and bulk density and documented the input of glaciagenic material into the lake basin. Over timescales of decades to centuries, downvalley sedimentation rates are controlled by glacial activity upvalley (Leonard, 1986). Therefore, periods of increased clastic sediment flux are interpreted to reflect glacial advances. An increase in inorganic carbon at calendar year ~1090 represents the initiation of the Little Ice Age and marks the beginning of glacial conditions. The period from ~1100-1400 is relatively stable however a rapid increase in clastic sediment flux and inorganic carbon ~1430 documents a change to a cooler climate and a return to glacial conditions. Peak clastic sediment flux values ~1850 reflect the maximum glacial extent of the Grinnell Glacier.

Regional records from the Rocky Mountains of the United States and the Canadian Rocky Mountains indicate that the Little Ice Age was driven by similar climate forcing mechanisms. This prolonged cold period was punctuated by intermittent periods of warmth and was not globally synchronous. Records from the Cordillera Blanca, in northern Peru (Tonry, 2010), European Alps (Fagan, 2000), and even Patagonia (Grove, 1988) display evidence of a sustained cold climate during the Late Holocene however, the precise timing does not correspond. Understanding the timing and magnitude of this cold period may help determine small scale forcing mechanisms that are driving climate change, and how these changes might propogate globally.

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