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Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Holli Frey
Symposium Convener
Union College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Christina Kelly
Symposium Proceedings Layout & Design
Office of Communication & Marketing
Scripps College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

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KECK GEOLOGY CONSORTIUM
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Robert J. Varga
Editor and Keck Director
Pomona College

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Pomona College
185 E 6th St., Claremont, CA
91711

Christina Kelly
Proceedings Layout & Design
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ADVANCE AND RETREAT OF GRINNELL GLACIER DURING THE LAST GLACIAL MAXIMUM, YOUNGER DRYAS, AND EARLY HOLOCENE AS RECORDED IN LAKE JOSEPHINE SEDIMENTS, GLACIER NATIONAL PARK, MONTANA

GRAYSON CARLILE, Whitman College
Research Advisors: Nick Bader and Bob Carson

INTRODUCTION

Determining the timing, magnitude, and spatial extent of climate shifts in the late Quaternary is an essential component of understanding controls on climate and predicting future climate change. Glacial extent is directly related to climate and can thus serve as a primary indicator of climate change (Mayewski et al., 2004). Small alpine glaciers respond to climate variability with time lags on the order of decades, making them particularly useful for characterizing these fluctuations (Jóhannesson et al., 1989). An improved understanding of alpine glacier dynamics may therefore offer additional insight into paleoclimate variability.

Lake sediments can preserve a high-resolution record of glacial fluctuations because glacial activity exerts a first-order control on the character of sedimentation in downstream lakes (Karlén, 1981). Because of this, lake sediments have provided some of the most complete records of glacial dynamics through the Holocene (e.g., Leonard and Reasoner, 1999; Munroe et al., 2012). Pristine, glaciated, sub-alpine environments, such as national parks throughout the North American Rockies, provide ideal localities from which we can extract such records.

Previous work on lake sediment cores in the Grinnell Glacier Valley in Glacier National Park, Montana has suggested that carbonate concentrations in lake sediments can be used as a proxy for increased activity of the Grinnell Glacier due to the presence of dolomitic limestone (Helena Fm., Fig.1) in contact with the glacier (MacGregor et al., 2011; Schachtman et al., in press). During periods of expected glacial advance, increased erosion of the Helena Formation and greater hydrologic energy resulted in delivery of greater amounts of carbonate to lakes within the drainage. In addition, the removal of upstream lakes as sediment sinks, and closer terminus position of the glacier, enhanced carbonate delivery. However, this previous work focused on cores only from Swiftcurrent Lake, the lowest in a series of four lakes in the drainage system of the Grinnell Glacier Valley (Fig. 1). The sedimentary records of three upstream lakes (Upper Grinnell Lake, Lower Grinnell Lake, and Lake Josephine) that act as sediment sinks have not been investigated for the late Pleistocene, a period when Grinnell Glacier was certainly larger than today. In order to better use carbonate as a tracer to constrain the timing of glacial fluctuations in the valley, we focus on the sedimentary record in an upstream lake to gain an understanding of how carbonate filters through the system during times of glacial advance and retreat.

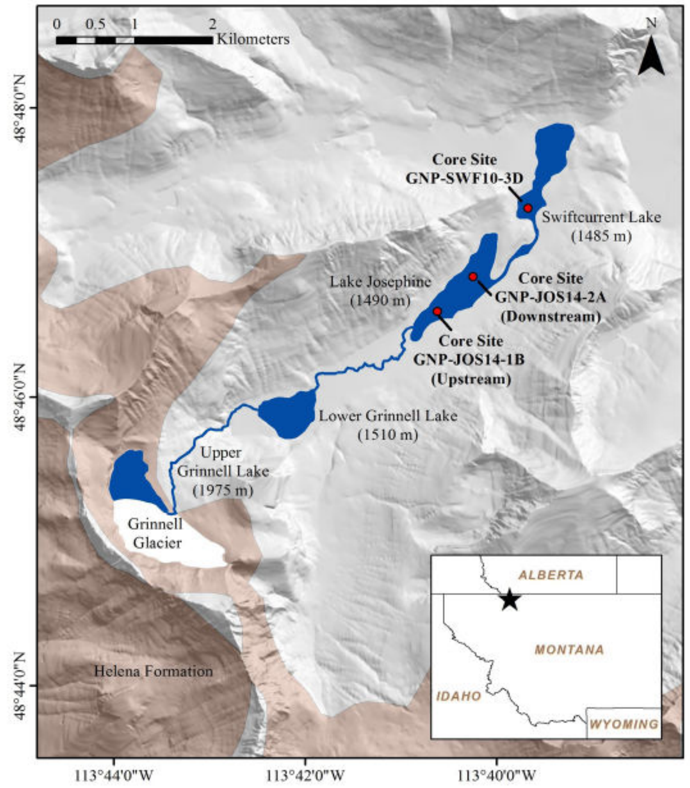

Figure 1. Map of the Many Glacier region of Glacier National Park, including the Grinnell Glacier and its upper drainage system. The lake coring site for this study (GNP-JOS14-2A) and two others (GNP-JOS14-1B, GNP-SWF10-3D) are indicated along with the extent of the Helena Formation (the source of carbonate sediment in the cores).

OBJECTIVE

We quantified detrital carbonate concentrations in a sediment core from Lake Josephine to test the hypothesis that carbonate concentrations in the lake sediments are a proxy for the size and erosional footprint of Grinnell Glacier. We are focusing on a time period between ~13,500 and 7,600 ybp, spanning the end of the Last Glacial Maximum, the Younger Dryas, and the beginning of the Holocene; this time period is bracketed by volcanic ash units of known age when northern hemisphere glaciers and ice sheets were advancing and retreating in response to climate change. Because Lake Josephine is farther upvalley than Swiftcurrent Lake, with one fewer lake acting as a sediment sink, we expect carbonate to be more abundant in Josephine and for it to record glacial behavior more sensitively than does Swiftcurrent Lake (Schachtman et al., in press).

GEOLOGIC SETTING

The Many Glacier region of Glacier National Park is situated in northern Montana, just east of the Continental Divide (Fig. 1). Grinnell Glacier terminates in Upper Grinnell Lake (1975 m above sea level, ASL), which drains into Lower Grinnell Lake (1510 m ASL), Lake Josephine (1490 m ASL), and Swiftcurrent Lake (1485 m ASL) successively. The drainage basin is underlain by the Middle Proterozoic Belt Supergroup, which is comprised primarily of sandstones, siltstones, and shales (Whipple, 1992). Grinnell Glacier sits on the Helena Formation, which includes dolomitic limestone, stromatolitic limestone, and calcitic argillite, and is likely the primary bedrock source of carbonate in the valley (Whipple, 1992; MacGregor et al., 2011) (Fig.1).

METHODS

Core JOS14-2A was collected from a floating platform in July 2014 using the Livingston-type coring technique (Wright, 1967, 1991). This core was collected downstream from another in Lake Josephine (JOS14-1B) in order to assess sediment transport within the lake. The core was logged, split, digitally photographed, and described using smear slides (Rothwell, 1989; Whipple, 1992) at the National Lacustrine Core Facility (LacCore), University of Minnesota. Gamma density, magnetic susceptibility, and color reflectance analyses were performed at the lab. The composite core (created from four separate overlapping core sections) was then sub-sampled at 1 cm resolution from ~ 428-693 cm below the sediment-water interface (Fig. 2).

This section of the core was chosen for analysis for two reasons. First, two volcanic ash deposits that were identified bracketed the section: the Glacier Peak G ash (13.71 ka - 13.41 ka; Kuehn et al., 2009) and the Mazama ash (7.63 ka +/- 150 years; Zdanovicz et al., 1999). The ash ages provided age constraints for the section in the absence of radiocarbon ages. Additionally, this period spans a known and climatically well-documented sequence of events: the late Pleistocene (a period of overall glacial retreat), the Younger Dryas (a cold period of abrupt onset when the glacier advanced; Schachtman in press), and warming into the Holocene (when Grinnell Glacier was likely

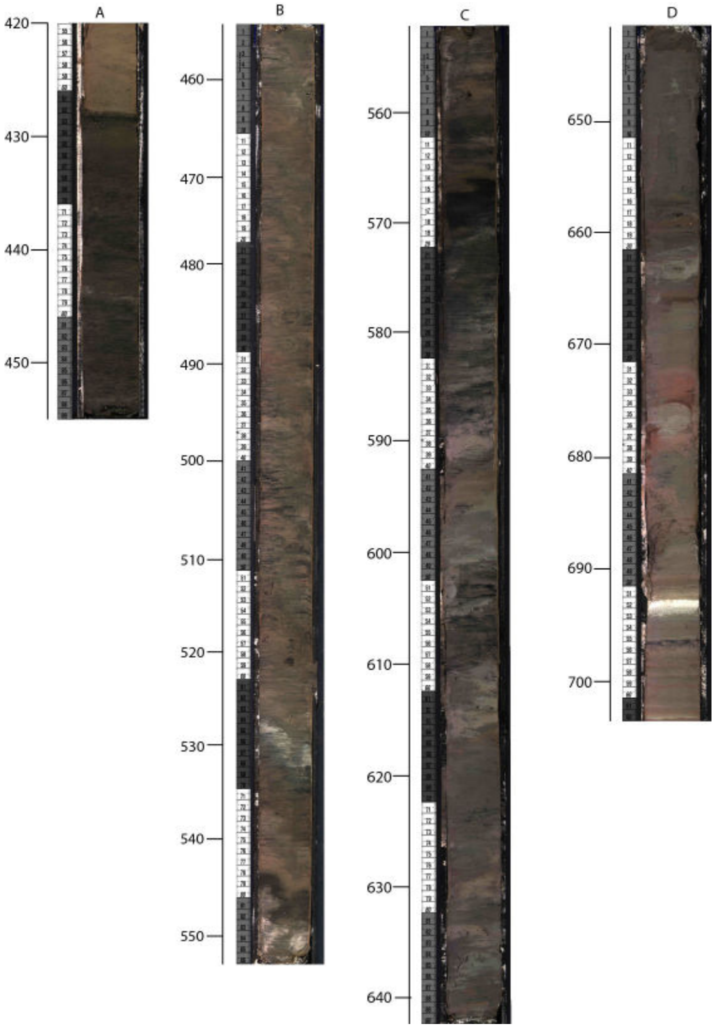

Figure 2. Image of the four core sections from Lake Josephine (GNP-JOS14-2A). The analyzed section spans from just below the homogenous tan Mazama ash at 428cm to just above the thin white Glacier Peak G ash at 693 cm.

smaller or non-existent; Carrara, 1987). This high degree of variability in climatic conditions is important to our understanding of how carbonate concentration is tied to glacier dynamics.

The 1-cm resolution subsamples from this section were analyzed at Whitman College for organic matter and carbonate mineral content using loss on ignition (LOI; Heiri et al., 2001). Percent organic matter and percent carbonate minerals were measured every centimeter using a Lindberg/Blue M 1100 Box Furnace. Samples were dried at 100 degrees Celsius, and then heated at 550ºC and 1000ºC to incinerate organic matter and carbonate minerals respectively. Samples were weighed between each burn and percentages of the two components were calculated using a Microsoft Excel macro developed at LacCore. This analysis was carried out in accordance with the standard operating procedure for LOI used at LacCore.

Using the average dates of 7630 ybp for the Mazama ash and 13500 ybp for the Glacier Peak G ash and assuming a constant rate of sedimentation, we created a simple age-depth model for the core. From this model, we estimated a sedimentation rate of ~0.4 mm/yr, and assumed that sedimentation rate was constant throughout.

RESULTS

Percent organic matter, % carbonate, and bulk density measurements are shown in Figure 3. Percent organic matter ranges between 1.4% to 8.9% (Fig. 3a), averaging ~ 4.2%; percent carbonate varies between 1.4% and 37% (Fig. 3b), averaging ~ 9.8%; and density ranges between 1.2 and 2.0 gcm^{-3} (Fig. 3c), averaging ~ 1.6 gcm^{-3}. We divide these data into four zones corresponding to significant changes in % carbonate values.

In Zone 1, % carbonate values decrease, hitting a low of 1.8% at ~12.6 ka. Organic values increase slightly between 13.5 ka - 13.3 ka but are generally stable, with values averaging ~3%. Bulk density decreases during this period, though less dramatically than % carbonate, reaching a minimum of 1.4 gcm^{-3} around 12.5 ka. Peaks within the downward trends of % carbonate and bulk density align.

In Zone 2, % carbonate values increase to a maximum of 37% with several prominent peaks (Fig. 3b). Percent organic values have two prominent peaks (7.4% and 8.9%) near the beginning of this time period, but fluctuate around 3%. Bulk density increases during this period, similar to increases observed carbonate. Variability in bulk density aligns with % carbonate except for a dramatic dip at 12.2 ka. This dip is likely due to partial sediment loss at the end of a core segment that occurred during extraction.

In Zone 3, % carbonate values drop substantially from the maximum reached in Zone 2, but peak around 10.1 ka. Average % organic matter increases by 2-3% between 11 ka and ~10 ka, and bulk density decreases during this period.

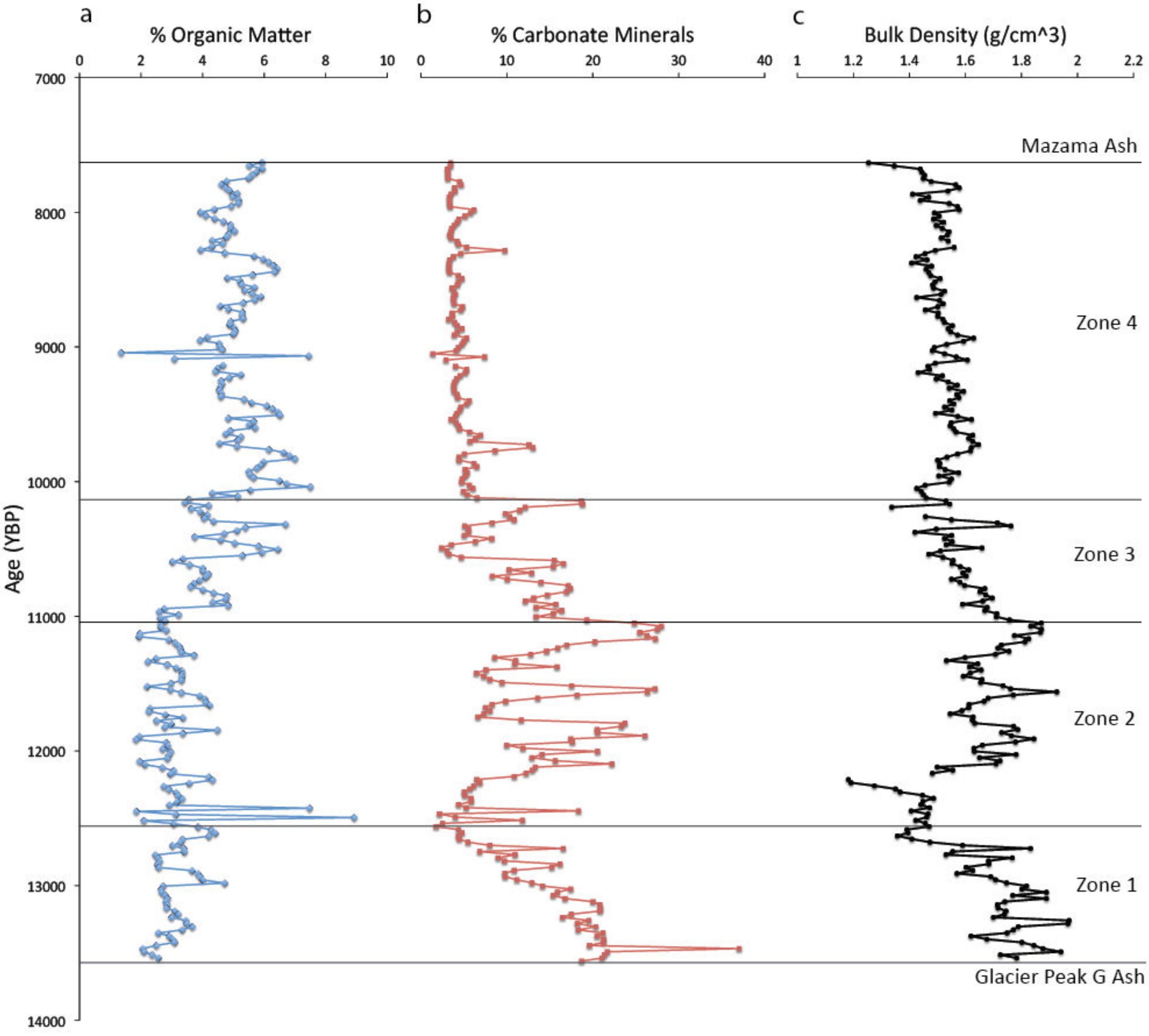

Figure 3. (a) Organic content (%), (b) Carbonate content (%), and (c) Bulk Density (gcm^{-3}) from core GNP-JOS14-2A. Mazama and Glacier Peak G ashes are identified by lines at 7600 YBP and 13500 YBP respectively. The graph is divided up into four zones based on significant trend changes in carbonate values.

In Zone 4, % carbonate values decrease from ~5% to ~3% over time, with only small variability. Percent organic values are highly variable, with a slight decrease in average over time from 6% to 5%. Average bulk density decreases slightly during this period, from 1.5 gcm^{-3} to 1.45 gcm^{-3}.

DISCUSSION

Decreasing carbonate values in Zone 1 (Fig. 3b) correspond to the Bølling-Allerød, a period of northern hemispheric warming in the late Pleistocene following the Last Glacial Maximum (Bartlein et al., 1998). Increasing % carbonate values in Zone 2 (Fig. 3b) overlap with the Younger Dryas - a period of known cooling and subsequent glacial advance in the region that lasted from ~12.8 ka - 11.5 ka (Muesheler et al., 2008). Finally, Zones 3 and 4 (Fig. 3b) line up with a period of warming following the Younger Dryas and climate stabilization into the Holocene (Beierle et al., 2003; Reasoner and Huber, 1999). This suggests that percentage of carbonate in Lake Josephine sediments reflects the position and extent of the Grinnell Glacier during the late Pleistocene and early Holocene. This claim is further supported by the fluctuations seen in bulk density that match closely with those seen in carbonate content. During periods of expected glacial advance, an increase in glacial flour production, along with an increase in summer melt, would increase the delivery of dense sediment to ice-proximal lakes. Bulk density may therefore also be used as a proxy for Grinnell Glacier extent. The lag in % carbonate and bulk density increase relative to the onset of the Younger Dryas may be explained by a later onset of Younger Dryas cooling in this area, a lag in glacial response to the onset of cooling, or uncertainties in our age model.

Comparison of % carbonate and % organic matter records reveals important information about the nature of sedimentation in the lake (Fig. 4). During the late Pleistocene (Zone 1), average % organic matter values are lower than during the early Holocene (Zone 4), which may reflect decreased organic production during colder time periods in the region. This hypothesis is supported by previous work showing a correlation between solar forcing and % organic matter in Swiftcurrent Lake between 7.6 ka and present (MacGregor et al., 2011). However, other work has shown that % organic matter decreases in alpine lakes during periods of ice advance because clastic sediment flux increases, effectively ‘swamping’ the organic content by increasing sedimentation rates (e.g., Leonard and Reasoner, 1999; Rodbell et al., 2008; Schacthman et al., in press).

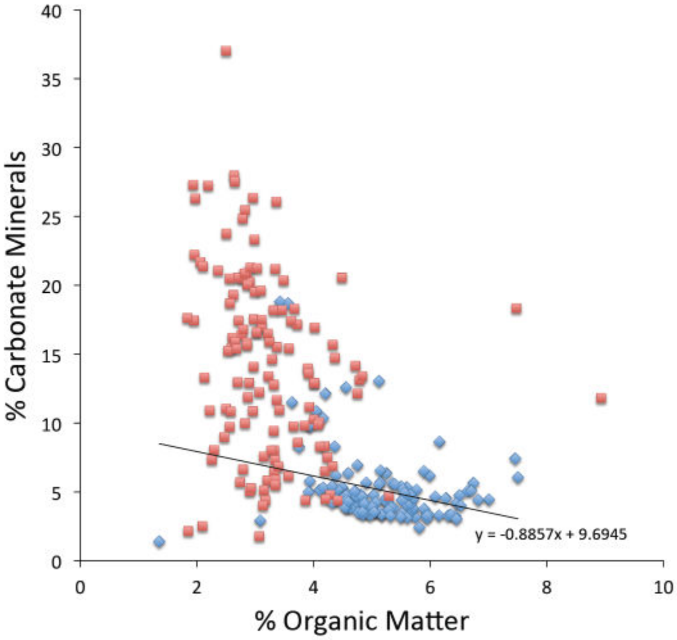

Figure 4. Organic content (%) vs. Carbonate content (%) from 13.5 ka to 7.6 ka. Points from the late Pleistocene (red points toward the left of the graph) are relatively spread out and anti-correlated. Points from the early Holocene (blue points toward the right of the graph) show a negative correlation (y= -0.8857x + 9.6945) between % organics and % carbonate.

The relationship between % carbonate and % organics shifts from one that is anti-correlated through the late Pleistocene and Younger Dryas (scattered red data points, Fig. 4), to one that appears positively correlated in the early Holocene (clustered blue data points, Fig. 4). This pattern suggests that increased sediment flux (reflected in increased % carbonate) may be diluting % organic matter during dynamic periods of glacial advance and retreat, leading to the anti-correlated relationship in the Pleistocene. In contrast, during periods of climate stability and decreased sediment flux (such as the Holocene), a distinct negative correlation between % organics and % carbonate indicates that during times of less dramatic sediment flux, smaller fluctuations in climate can be correlated with trends in % carbonate versus % organics: cooler periods yield higher % carbonate values (due to increased erosion and sediment transport) and lower % organic matter values (due to solar forcing). Further age constraints and mass accumulation rates are needed to refine the relationship between % organic matter and % carbonate and determine if indeed clastic swamping controls % organic matter during cooler periods.

Comparison of carbonate between this site (GNP-JOS14-2 (Site 2)), an upstream site in Josephine (GNP-JOS14-1 (Site 1); Clippinger, this volume), and a third in downstream Swiftcurrent Lake (GNP-SWF10-3 (Site 3); Schachtman et al., in press) (Fig. 5), provides further support for carbonate content as a proxy for glacial fluctuations. Sedimentation rates vary greatly between the two sites in Lake Josephine with rates ~31% higher at site 1 (more proximal to the source). While these sites have different amounts of carbonate and varying magnitudes of fluctuation in carbonate, the fluctuations generally follow the same trends temporally, despite different rates of sedimentation.

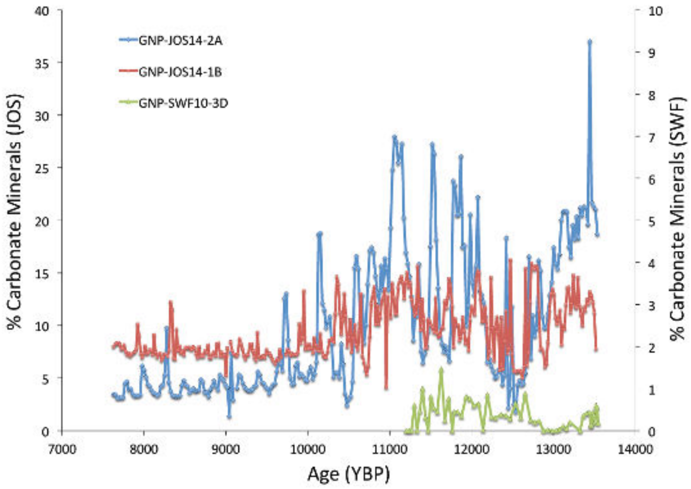

Figure 5. Carbonate content (%) in GNP-JOS14-2A, GNP-JOS14-1B, and GNP-SWF10-3D. While values are variable between GNP-JOS14-2A and GNP-JOS13-1B, they follow the same general trends. Percent carbonate values in GNP-SWF10-3D are much lower. However, the primary time frame where an inorganic carbon signal is picked up (12.7 ka - 11.3 ka) corresponds to the increase in % carbonate seen in the other two records.

The overall higher values of % carbonate between 13.7 and 10.2 ka (Zones 1-3; late Pleistocene) at site 2 are initially surprising considering it is more distal to the sediment source than site 1. As carbonate is sourced from the cirque of the Grinnell Glacier, it is likely fine-grained by the time it reaches Lake Josephine as it has been ground into glacial flour and coarser sediments have settled in Lower Grinnell Lake. Because of this, we might expect that during times when the glacier was closer to or terminating in the lake (13.5 ka - 10.5 ka), higher hydrologic energy from increased meltwater might have swept finer sediments farther out into the lake (toward site 2) before they settled, while coarser sediments settled out at site 1. Shallower conditions at site 1 may have also contributed to finer carbonates being swept downstream by meltwater currents. Higher values at site 1 during the early Holocene could be explained by a substantially smaller and more distal glacier with lower rates of erosion, sediment production, and lower melt water discharge, yielding calmer conditions more conducive to carbonate settling at this site. Low % carbonate values in Swiftcurrent Lake compared to Lake Josephine reflect the efficient sediment trapping ability of Lake Josephine. However, even in the Swiftcurrent record there are values as high as 1.5% during the Younger Dryas, when % carbonate values increase at both sites in Lake Josephine. While the values in Swiftcurrent Lake rise slightly earlier than in Lake Josephine, this can likely be explained by variance in sedimentation rates that increase uncertainties in both age models during this time period.

CONCLUSION

Analysis of lacustrine sediments from Lake Josephine in the Grinnell Glacier Valley, Glacier National Park, Montana, reveals that carbonate concentrations are a good proxy for glacial extent within the valley during the late Pleistocene and early Holocene. Carbonate percentages in sediments decrease in concert with warming trends during the late Pleistocene (when we would expect the glacier to be receding), increase throughout the Younger Dryas cooling (when we would expect the glacier to be advancing), and decrease and stabilize in to the early Holocene when climate warmed and stabilized. Similar trends in bulk density support this conclusion. Additionally, anti-correlated inorganic carbon versus organic carbon concentrations during the Pleistocene contrasted with negatively correlated concentrations in the Holocene indicate that the organic signal may be swamped during periods of increased sediment flux associated with glacial advance.

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