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

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Research Advisor: Kelly MacGregor

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INORGANIC CARBON IN ALPINE LAKES AS A PROXY FOR GLACIER DYNAMICS DURING THE LATE HOLOCENE, GLACIER NATIONAL PARK, MONTANA

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Research Advisor: Kelly MacGregor

INTRODUCTION

Glaciers play a significant role in shaping the surface of our planet. Sensitive to variations in climate, alpine glaciers grow and shrink in response to temperature and precipitation changes, which in turn affects glacial erosion and sediment transport (e.g., Licciardi, 2004). Proglacial sedimentary deposits like moraines preserve the position of glaciers in the past, and are therefore indicative of past climate conditions (e.g., Benn and Evans, 1998). Sediment sinks such as proglacial lakes provide a more continuous record of sedimentation than do terrestrial deposits, although unraveling the relationships between climate change, glacier response, and subglacial erosion and transport of sediment can be complicated (e.g., Karlén, 1976; Leonard, 1997; Loso, 2006).

Grinnell Glacier valley in Glacier National Park, Montana, provides a natural laboratory for understanding the relationships between climate, ice dynamics, subglacial erosion, and sediment transport and deposition. Short timescale 'live' records of ice behavior, as documented through historical photographs and observations, help link regional climate change to local ecological and environmental change in Glacier National Park (Dightman and Beatty, 1952). Photo evidence and documented observations show that Grinnell Glacier has been retreating since 1850, the end of the prolonged period of cooling known as the Little Ice Age (LIA) (Carrara, 1989; Johnson, 1980; Krimmel, 2002). This makes Grinnell Valley an ideal location for studying variability in lake sedimentation because the size of the glacier is known over the past ~160 years. Because Grinnell Glacier resides in a National Park, there is heightened public interest in how it might change in the future.

In the Grinnell Glacier and adjacent Swiftcurrent valleys, sediment cores have been collected and studied in three of the four proglacial lakes downstream of Grinnell Glacier (MacGregor et al., 2011a,b) (Schachtman et al., in press). Several studies have focused on correlating the sedimentary record and the behavior of Grinnell Glacier over time, helping to clarify our current understanding of climate variability in this region reaching as far back as the Pleistocene (e.g. Anderson et al., in review; Schachtman et al., in press). Cores from the two most distal lakes in the valley, Lake Josephine and Swiftcurrent Lake, have been analyzed for carbon content. Inorganic carbon (carbonate) is almost exclusively detrital dolomite sourced by the stromatolitic dolostone member of the Siyeh/Helena Limestone into which Grinnell Glacier is currently eroding. No dolomite was found in Swiftcurrent Lake during the LIA (Anderson et al., in review). Organic carbon has been investigated as well. MacGregor and others (2011a) found in Swiftcurrent Lake that organic carbon can be used as a proxy for solar forcing, while more recent work (Schachtman et al., in press) suggests organic carbon is inversely correlated with sediment flux during times of cooler climate and enhanced glacier activity. In this project, I further explore organic and inorganic carbon variability in lake sediments as a proxy for the position and behavior of Grinnell Glacier. My research shows that sedimentation rates are higher in the upvalley, ice proximal part of Lake Josephine, with increases in carbonate concentrations during the LIA. Organic carbon concentrations increase in the last ~100 years during a period of measured warming in the region.

FIELD SETTING

Glacier National Park is located in the northern U.S. Rocky Mountains, east of the Continental Divide. The 36 sq km Grinnell Valley is located in the northeastern part of the Park, and is home to the Grinnell Glacier, and a chain of four proglacial lakes: Upper and lower Grinnell Lakes, Lake Josephine, and Swiftcurrent Lake (Fig. 1 of project summary). The drainage basin is underlain by the Middle Proterozoic Belt Supergroup. Grinnell Glacier currently sits on top of and erodes the Siyeh/Helena Limestone, a unit primarily composed of stromatolitic dolostone, as well as calcitic argillite (Whipple, 1992). These are the only known sources of detrital dolomite and calcite in the valley.

Meltwater from Grinnell Glacier flows directly into upper Grinnell Lake at an elevation of ~2,100 m, filling the upper cirque basin. It then drains into lower Grinnell Lake at an elevation of 1536 m, over a ~460 m bedrock step. Water moves ~2 km from lower Grinnell Lake through Grinnell Creek into Lake Josephine at an elevation of 1488 m, with only ~50 m of elevation change. Based on bathymetric measurements, a coring site was chosen ~100 m from shore at a depth of 8.4 m in the upvalley portion of Lake Josephine, at a location upstream of previous core sites in Lake Josephine and Swiftcurrent Lake. The land elevation here is 1487-1491 m.

METHODS

One continuous 197 cm core was synthesized from a set of overlapping cores retrieved from an upstream site in Lake Josephine in July 2014. Two separate core holes at this site ~1 m adjacent were selected to ensure collection of a continuous sediment record. Coring interval depths in each hole were offset to ensure that any gaps between core attempts were accounted for. Square rod piston coring devices were utilized to retrieve sediment. The continuous sediment record was constructed by visually correlating overlapping cores from adjacent holes (e.g., using stratigraphic markers, color banding, texture).

After collection in the field, all cores were transported to LacCore, University of Minnesota. We measured magnetic susceptibility and core density using a Geotek MSCL-S; cores were then split, cleaned, described, and digitally imaged using a Geotek CIS. Smear slide analyses (microscopic core descriptions) were done on representative sections of each core to provide semi-quantitative compositional information. The 197 cm of the continuous core were sampled at 1 cm intervals and freeze-dried for coulometric and XRD analysis.

Carbon coulometry was performed on all 197 samples using the coulometer (UIC CM440-036) at Macalester College. Total carbon (%TC) was determined using a CM5200 furnace. Between 30 and 40 mg of each sample was weighed into an aluminum boat and heated to 950°C. Percent TIC was determined for all samples using the CM5240 acidification module. Again, between 30 and 40 mg of each sample was weighed into capsules and dissolved during the analysis to determine %TIC. The carbon dioxide gas produced by combustion or dissolution moves through a coulometer cell and is absorbed quantitatively by the cell solution to determine carbon concentration. Total organic carbon (%TOC) values were calculated by subtracting %TIC from %TC.

X-ray diffractometry (XRD) was conducted every 8th cm on a Panalytical X'Pert Pro MPD; after looking at primary results, 30 additional samples were run for a total of 55 samples. Scans were utilized to determine dolomite and calcite presence/absence.

RESULTS

Total Inorganic Carbon

Percent TIC values range from .042% to 1.8% (Fig. 1b). Values are variable from 197 cm through 76 cm, and show a gradual increase. Percent TIC decreases abruptly at 76 cm and remains low through ~ 50 cm. There is a notable increase around ~18 cm, and %TIC gradually decreases through the top of the core.

Total Organic Carbon

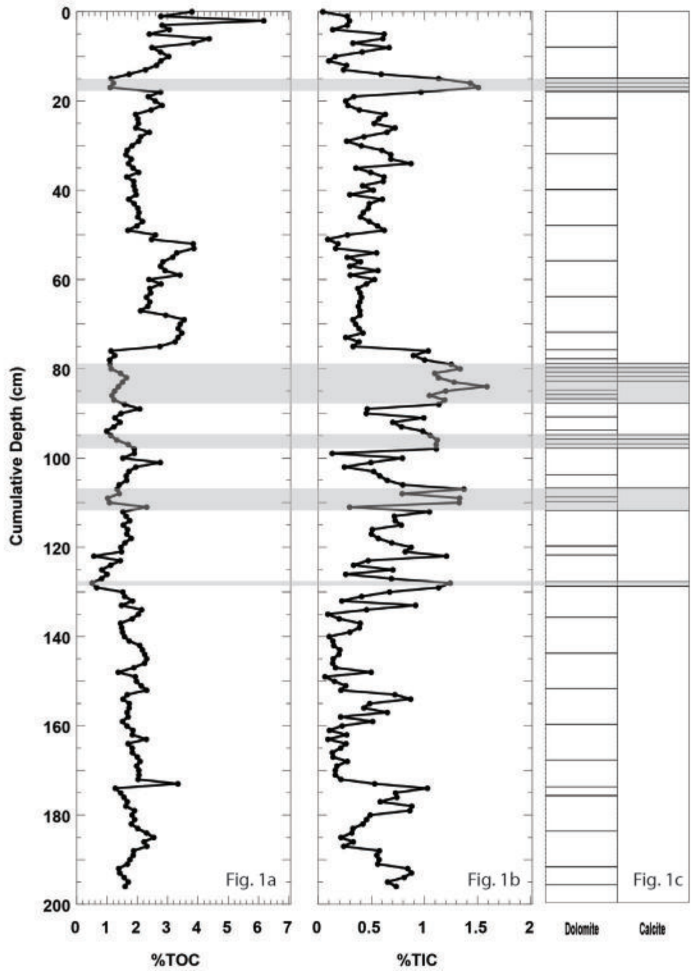

Figure 1. Figure 1a shows percent organic carbon with respect to sediment core depth (cm). Figure 1b shows percent inorganic carbon with respect to sediment core depth. Figure 1c shows XRD presence of dolomite and/or calcite with respect to sediment core depth, indicated by black bars. Grey boxes highlight intervals where calcite is identified.

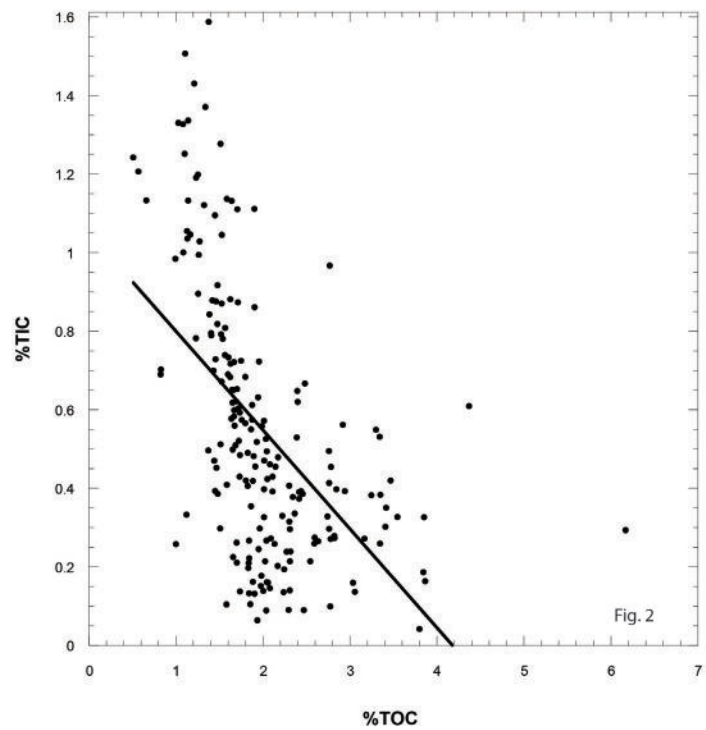

Figure 2. Scatter plot showing %TOC vs. %TIC. Linear best fit equation is imposed and shows the anticorrelation between organic carbon and carbonate.

Percent TOC ranges from 0.51% to 6.9%, with most values between ~1-4% (Fig. 1a). From 197 cm to about ~76 cm, values remain low and generally steady. At ~76 cm, %TOC increases sharply and remains high until ~50 cm. At 18 cm, an abrupt decrease is followed by a gradual increase toward the top of the core. Higher %TIC values are in associated with lower %TOC values, and vice versa (Fig. 1, Fig. 2).

XRD

Dolomite was identified in all samples analyzed (Fig. 1c). In sections of the core with low %TIC (0-15 cm, 20-80 cm, and 130-197 cm), calcite is not found. Calcite is present in ~36% of the samples analyzed and is found only when %TIC is above average (.55%), with the exception of one sample at ~128 cm (Fig. 1c, grey boxes). Smear slide analyses show carbonate grains are subrounded with rough edges, suggesting that grains are detrital.

DISCUSSION

Inorganic carbon in Lake Josephine is primarily allochthonous detrital dolomite, sourced from the dolostone surrounding Grinnell Glacier. The presence of dolomite (MacGregor et al., 2011a) and higher %TIC (Schachtman et al., in press) in the Swiftcurrent core occurs during periods of the Late Pleistocene and early Holocene only when northern hemispheric climate was generally cool, and is likely associated with a combination of larger glacier extent and hydrologic activity. Detrital dolomite was effectively transported through the system to downvalley lakes when Grinnell Glacier was more expansive (extended over upvalley lakes) and when hydrologic energy was higher (high summer runoff). Low %TOC values are likely the product of organic carbon dilution due to contemporaneous high sediment influx, at least during the end of the Last Glacial Maximum and Younger Dryas (Schachtman et al., in press). In Lake Josephine, increased %TIC was associated with increased glacial extent and the removal of Upper Grinnell Lake as a sediment sink during the LIA (Anderson et al., in review). Higher %TIC values were also measured in Lake Josephine sediments deposited in the last century, despite a greatly reduced glacier footprint, likely a result of high summer meltwater runoff due to warmer summer temperatures. These findings suggest that periods of higher %TIC in the core reflect times when the glacier was larger (e.g., the LIA) or when hydrologic energy was higher and therefore sediment transport capacity is high.

Low %TOC values have been shown to be the product of organic carbon dilution due to contemporaneous high sediment influx in proglacial lakes (Leonard & Reasoner, 1999; Rodbell, 2008). Sources of organic carbon are variable and could be autochthonous matter from within the lake or from hillslopes and shorelines. C/N and carbon isotope data have shown that organic carbon in the lake is increasingly lacustrine algal, and less terrestrial, over the past ~200 years (Anderson et al., in review). The inverse relationship between %TIC and %TOC may be the result of a swamping signal; organic carbon concentrations have been shown to decrease as the result of dilution by the high clastic sediment input associated with high carbonate concentrations (e.g. MacGregor et al., 2011a; Karlen, 1976; Leonard, 1997; Munroe et. al., 2012). Alternatively, this signature could reflect a decrease in primary productivity in the lake during cooler periods (Munroe et. al., 2012). While the inverse correlation suggests that %TIC controls %TOC values, it is also possible that there is simply an increase in the total amount of organic carbon being deposited in the lake in the last century as climate warmed. Once lead-210 age controls on the top section of the core are completed, mass accumulation rates can be calculated and the relationship between %TOC and %TIC resolved.

Dolomite was present in all XRD samples, suggesting erosion and/or transport of the Siyeh/Helena Limestone is an important source of sediment to Lake Josephine. Smear slide analysis suggests that calcite is also detrital; sources of calcite could be the calcitic argillite member of the Siyeh/Helena Limestone, but work to constrain the source is ongoing (Stephens, this volume). Calcite was only found when %TIC was high, and no calcite was identified in the downstream Josephine core spanning ~1000 years (Anderson et al., in review). Calcite was not present in the Swiftcurrent Lake core except during the Late Pleistocene, when the Grinnell Glacier terminus was likely much closer to Swiftcurrent Lake. This suggests that calcite transport is linked to dolomite transport, but apparently is not mobilized and transported as readily. This could be the result of calcite being sourced from a specific part of the unit, perhaps higher up on the headwall, therefore requiring a much greater glacier thickness to access it.

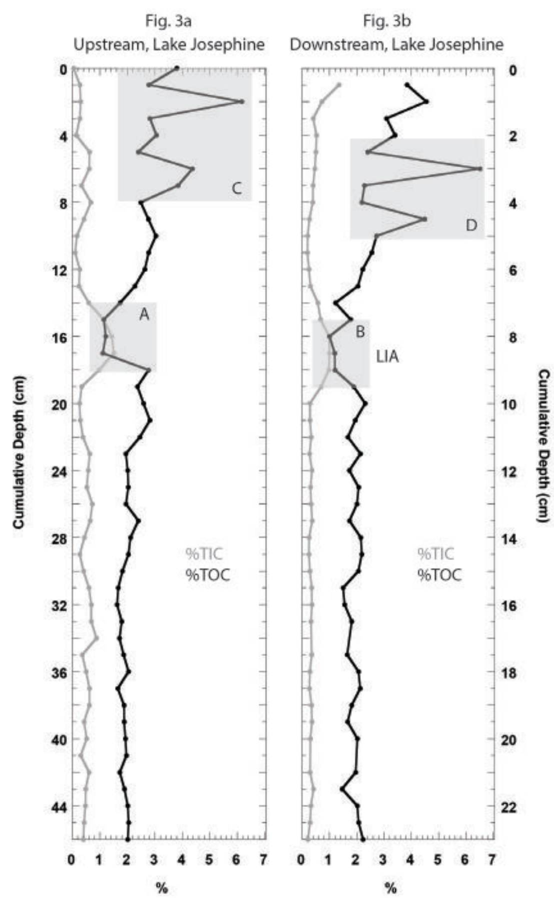

Figure 3. Figure 3a shows percent organic carbon (black) and percent inorganic carbon (gray) in the top 46 cm of a sediment core in the upstream portion of Lake Josephine, retrieved in 2014. Figure 3b shows percent organic carbon and percent inorganic carbon in the top 23 cm of a sediment core in the downstream portion of Lake Josephine, retrieved in 2010. Grey boxes represent areas of apparent correlation between upstream and downstream cores.

Inorganic and organic carbon concentrations were reported from a core taken from a site farther downlake in Lake Josephine (Fig. 3b; Anderson et al., in review). Percent TIC and %TOC values were similar between the two sites, with slightly higher %TIC concentrations upstream. There are two intervals in the %TOC records that appear to correlate well (Fig. 3a, b; grey boxes A-C). A dip in %TOC occurs between 18 and 14 cm (Fig. 3a, gray box A), and is tied to an increase in %TIC in both records (Fig. 3a,b; gray boxes A and B). The age model for the downstream core shows that this represents the LIA (~1700-1900 CE; Anderson et al., in review). An increase in %TOC is also documented near the top of the core, and is similar to that found downlake (Fig. 3a,b; gray boxes C and D). Notably both %TOC and %TIC show limited variability between 20-46 cm/10-23 cm. It is plausible that these sections are showing the same variability in deposition of clastic material; therefore it may be reasonable to correlate them in time. This would suggest the deposition rate at the upstream site is twice that of the downstream site (.4mm/yr upstream and .2mm/yr downstream). This will be confirmed when lead-210 ages are received.

Broadly, the data from both Lake Josephine cores show a very similar pattern of variability and amount of %TIC and %TOC. Apparent correlated events appear higher stratigraphically in the upvalley core than in the downvalley core (Fig. 3a,b; grey boxes A-D); we argue that this is the result of higher rates of sedimentation in the upstream portion of Lake Josephine. We expect higher sedimentation rates at the upvalley site because of the closer proximity to the glacier and inlet stream from lower Grinnell Lake. Percent TOC increases and decreases dramatically near the top of both cores in a similar fashion; the pattern occurs between 0 and 8 cm upstream and between 2 and 5 cm downstream. Sedimentation rates are lower downvalley and cause the signatures of fluctuation and events to appear more condensed.

CONCLUSIONS

Key Results:

1. Percent TIC and %TOC are anticorrelated during the presumed LIA, suggesting that glacial production and/or transport of clastic sediment controls the %TOC record in this lake, This relationship does not hold for the youngest part of the core, where %TOC actually increases despite modest decreases in %TIC; this could be attributed to more lacustrine algal production as a result of warmer temperatures, as suggested by Anderson and others (in review).

2. Increases in %TIC correlate well with those of a downvalley Lake Josephine core with age controls. If the age model holds true, %TIC increases occur during the LIA, presumably due to glacial advances and/or a more erosive glacier, as well as a reduced number of sediment sinks. This supports the interpretation that %TIC reflects glacier size/position.

3. If the age model estimate is correct, it implies the sedimentation rate is about twice as high at the upvalley Lake Josephine site as compared to the downvalley site over the last ~1000 years.

4. Dolomite is more abundant than calcite in the core. It is unclear why calcite is only present when %TIC is higher or why calcite is not present at the downstream site in Lake Josephine nor in Swiftcurrent Lake before the Pleistocene. Further work to investigate the sources of dolomite and calcite is being conducted (Stephens, this volume); grain size and smear slide analyses may also help resolve the differences in erosion and transport of carbonate grains in the valley.

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