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Climate versus geological controls on glacial meltwater micronutrient production in southern Greenland

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ABSTRACT

Low concentrations of micronutrients in subarctic North Atlantic surface waters limit phytoplankton growth. Iron, phosphorous, and silicon are all potentially bio-limiting nutrients; iron is the most well documented in the subarctic North Atlantic. Manganese, nickel, copper and zinc are also essential trace metals for phytoplankton cell function. However, the spatial and temporal variability in the flux of these elements to the subarctic North Atlantic is undercharacterized. Here we show new data from the meltseason peak in 2013 indicating that glacial meltwater from the southern tip of Greenland has elevated dissolved major and trace metal concentrations compared to glacial meltwater draining shorter melt season glacial catchments to the north. Fe concentrations range from 0.13 to 6.97 μM, Zn from 4 to 95 μM, and Si from 4 to 36 μM, all higher than the depleted surface waters of the subarctic North Atlantic. Measured hydrochemical data modeled by PHREEQC indicates meltwater is undersaturated in pyrite and silicate phases but supersaturated with respect to oxyhydroxides, hematite and goethite, all phases that precipitate Fe as colloids, of which the nanoparticle phases should remain biologically available. The variability in geologic units between the sites indicates that subglacial lithology is a minor but not the dominant control on meltwater chemistry. The disparity in concentrations is directly correlated with climate, and an extended melt season, suggesting that future warming in Greenland will lead to increased trace element, and potential micronutrient, flux to the subarctic North Atlantic surface waters.

1. Introduction

The major controls on chemical and nutrient fluxes from Greenland are undetermined despite their importance in elucidating paleo-ice sheet dynamics and climate feedback processes. Whereas the Antarctic represents the largest icesheet present on Earth, the Greenland ice sheet (GrIS) has been described as equally sensitive to abrupt climate change and thereby prone to major contributions to sea-level rise, estimated to be as much as 0.8 m by the end of the century (Pfeffer et al., 2008). The magnitude and timing of polar ice sheet mass loss and the form it will take over the next century is still a matter of contention (Pachauri and Reisinger, 2007; Pfeffer et al., 2008). Recent models of the GrIS during the last interglacial, the time period most analogous to future climate change, suggest that most of the ice loss was in southern Greenland. In the last decade warming has accelerated surface melting on the GrIS and during record melt years in 2007 and 2010, correlated with record world-wide high temperature anomalies, most of the melt occurred in southern Greenland (Fig. 1a, Sasgen et al., 2012).

Recent measurements from the GRACE satellite indicate that ice mass loss is non-uniform and that the seven drainages (Fig. 1b) within the ice sheet have different responses to regional and global climate change (Rignot et al., 2011; Sasgen et al., 2012). Surface air temperature, melt water propagation to the bed, and ice thickness will determine the amount of water at the ice-rock interface: subglacial meltwater is derived from (1) surface meltwater that drains to the bed through crevasses and moulins in the ablation zone and (2) basal meltwater where the ice thickness and/or ice temperature is high enough to induce pressure melting (Cuffey et al., 1999; Bell, 2008; Cuffey and Paterson, 2010). While the GrIS is the warmest of the three polar ice sheets, and subsequently has the most surface melt propagation to the bed (Joughin et al., 2008; Das et al., 2008), the outlet glaciers from the GrIS vary in local temperature and ice thickness. Therefore, ice and subglacial water interaction with the underlying substrate should also vary regionally.

The subglacial environment can be viewed as a flow-through reactor (Anderson, 2005): meltwater passing over and through till

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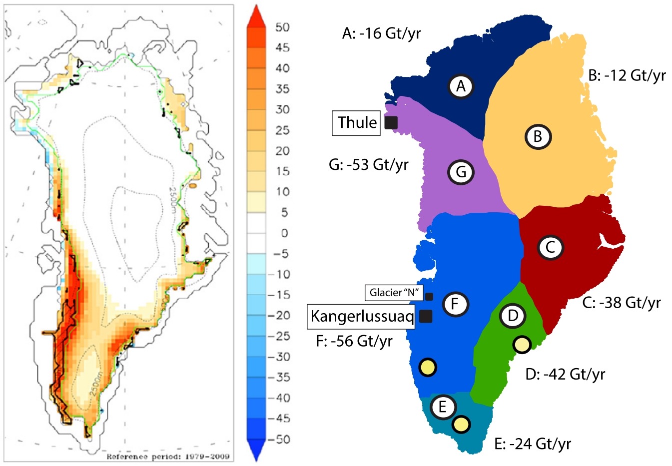

Fig. 1. (a) Greenland melt anomaly, measured as the difference between the number of days on which melting occurred in 2010 compared to the average annual melting days from 1998–2009 (Tedesco et al., 2011). The areas with the highest amounts of additional melt days appear in red and areas with below-average melt days appear in blue. (b) The seven drainages of Greenland (A–G) with annual mass loss from each watershed indicated (Sasgen et al., 2012). Black squares are the field sites for which there is flux data, yellow sites are the new locations in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

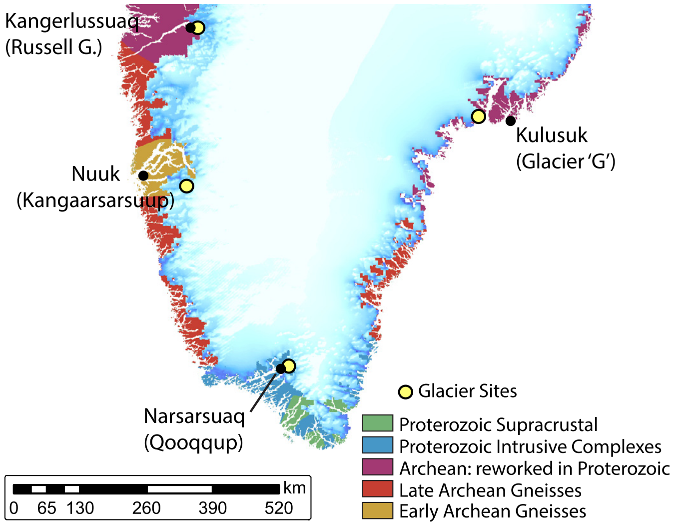

Fig. 2. Regional geology of southern Greenland with sampling sites indicated (yellow dots) and closest settlements (black dots). Sampling locations for the three new sites are land terminating outlet glaciers with single meltwater channels that drain to fjords connected to the North Atlantic. The Russell and Isunnguata Germa glaciers near Kangerlussuaq sit atop Late Archean gneiss reworked in the Proteroizoic. The Kangaarsarsuup Sermia glacier, ∼45 km from Nuuk, sits atop mixed Late Archean gneiss and Proterozoic supracrustal bedrock, but is in close proximity to Amitsoq Gneiss (3.8 Ga). The meltwater channel for unnamed glacier, Glacier "G", ∼60 km from Kulusuk, rests on mixed Late Archean gneiss and Proterozoic supracrustal bedrock but the ice sheet margin in the region has bedrock composed of Proterozoic intrusives (primarily granodiorite and granite). The terminus of Qoorqup Sermia, ∼8 km from Narsarsuaq, rests on part of the Garder Intrusive Complex but the ice sheet is primarily resting on granite/granodiorite (1.8 Ga). See Fig. S1 and Henriksen et al. (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and bedrock surfaces and subsequent chemical weathering fluxes from this water–rock interaction. This meltwater environment also contains the necessary ingredients to support active communities of microorganisms that influence the dissolution of cycling of nutrients: water, organic matter and fresh rock flour from glacial grinding (Bhatia et al., 2013; Bottrell and Tranter, 2002; Skidmore et al., 2005; Tranter et al., 2002a; Wadham et al., 2004). The water–rock interaction – driven by local climate – and bedrock geology should influence the composition of the hydrological outputs (Anderson, 2007; Mitchell and Brown, 2008; Raiswell, 1984; Sharp et al., 1995; Tranter et al., 2002b) and yet are not measurable via remote observations. The subsequent downstream export and discharge of water from glacial and sub-glacial catchments to oceanic environments has the potential to stimulate ocean primary production if the water contains significant quantities of biologically limiting micronutrients (Raiswell, 1984; Raiswell et al., 2008; Wadham et al., 2010; Bhatia et al., 2013).

In the Arctic, macronutrients are depleted on seasonal cycles with lower productivity after the spring phytoplankton bloom in open water, and higher near banks or in shallow waters (Smith and Sakshaug, 2004), presumably from continental weathering sources. The micronutrient iron (Fe) is known to be biologically limiting for phytoplankton in the surface ocean of the subarctic North Atlantic (Nielsdóttir et al., 2009). Copper (Cu), cobalt (Co), zinc (Zn), nickel (Ni), manganese (Mn) and silicon (Si) (for diatoms) are also essential for metabolic processes in surface ocean organisms (Morel et al., 1991, 1994, 2003; Coale, 1991; Kremling and Streu, 2001), show depletion in the surface subarctic Atlantic ocean (Pohl et al., 1993; Kremling and Streu, 2001; Saager et al., 1997), and are potentially biologically limiting or co-limiting (Morel et al., 1991, 1994; Bruland et al., 1991). As Moore et al. (2013) point out, it was only through improvements in analytical techniques, experiments and sampling that Fe biological limitation was ultimately proven; the low total number of measurements, spatial distribution, and their impact on the organisms limits our understanding of the importance of these other biologically significant trace metals in the subarctic Atlantic Ocean.

Here we investigate three new glacial catchments, across three geological terrains of southern Greenland and different regional climates, to assess the variability in micronutrient concentrations sourced from Greenland glacial meltwater. Each GrIS drainage area (Fig. 1b, A–G) has a different combination of geology and climate that should result in variable hydrogeochemistry. Previous characterization of meltwater from Greenland has been limited to a small region in drainage F and G, noted in Fig. 1b: the Kangerlussuaq area glaciers and Glacier 'N' (Bhatia et al., 2011, 2013; Ryu and Jacobson, 2012; Statham et al., 2008). The new glacial catchments described here include sites that extend south from the previously studied sites in western Greenland to the southern tip of Greenland, having an extended melt season, and to eastern Greenland, having a short melt season.

2. Field area and sampling

Each of the new sampling sites is located at the terminus of an outlet glacier (12–40 km in length) directly connected to the GrIS, and sits on bedrock of different age. In addition to the three new sites, we also collected samples from the Kangerlussuaq region (Isunnguata and Russell Glaciers) in order to provide a measure of comparability between our techniques and those made by other groups. We note that the nature of the discharge from the Kangerlussuaq glaciers where meltwater drains into a series of side lakes and streams before aggregating in a large river results in hydrochemistry of water collected at the terminus being a combination of glacial and fluvial/limnological processes. Therefore we make comparisons between samples collected from the same marginal sites where water is purely glacier-sourced.

The exposed geology in southern Greenland is Precambrian shield, characterized by the accretion and exposure of five primary Proterozoic and Archean terrains (Fig. 2, Henriksen et al., 2009). Early Archean gneisses, including the Isua supergroup, are exposed in a small wedge in the Nuuk vicinity. Late Archean terrains are sandwiched between Proterozoic terrains: to the north reworked