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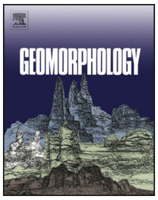

Chemical weathering trends in fine-grained ephemeral stream sediments of the McMurdo Dry Valleys, Antarctica

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ABSTRACT

We investigated chemical weathering trends within the fine-grained (<63 μm; silt and clay) fraction of sediments collected from meltwater streams emanating from glaciers in the McMurdo Dry Valleys (MDV; Wright and Taylor Valleys) by integrating grain size, BET surface area, and whole-rock geochemistry. While both valleys currently host cold-based glaciers, the sediment underlying the ephemeral glacial streams was deposited under differing glacial conditions. In Wright Valley (Clark Glacier stream), Brownworth and Trilogy drifts were deposited via cold-based glaciation, whereas the Ross Sea drift that underlies Delta Stream in Taylor Valley likely reflects contributions from wet-based ice. Wright Valley stream sediments are typically coarser grained and have a higher silt content as compared to Taylor Valley sediments. These sediments consist primarily of pyroxenes, quartz, and feldspars, with the percentages of pyroxenes and quartz systematically increasing downstream. The percentage of phyllosilicates ranges from 4 to 18% and decreases with downstream distance. In contrast, Taylor Valley sediments (Delta Stream) are finer-grained and exhibit lower percentages of both pyroxene and quartz and a significantly higher percentage of phyllosilicates (30–43%). Concentrations of all mineral phases remain relatively consistent in abundance with downstream transport in the Delta Stream transect as compared to Clark Glacier stream sediments. Standard chemical weathering indices, such as the Chemical Index of Alteration (CIA), indicate that chemical weathering is occurring within the silt and clay fractions of Antarctic stream sediments and is particularly pronounced in Delta Stream sediments that have BET surface area measurements >40 m^2/g. Utilization of MFW (mafic-felsic-weathered) and A-CN-K (Al_2O_3-CaO + Na_2O-K_2O) plots, however, are more effective in discerning the extent and nature of chemical weathering in these stream systems. Ca and Na depletion observed within the sediments exhibiting the highest surface area in Delta Stream suggest that chemical weathering may result in pitting and/or incongruent dissolution of pyroxenes and feldspars, as well as the development of amorphous and/or nanophase weathering products. In contrast, Clark Glacier stream sediments do not have similar leaching trends in the fine-grained sediment fraction and exhibit minimal weathering overall. This may suggest that fine-grained material is being trapped on top of the Clark Glacier surface and has not yet been transported into the weathering environment of the hyporheic zone due to timing of sampling. Alternatively, complete dissolution of very fine-grained sediment could be occurring in this stream transect, and is therefore not preserved in the fine sediment fraction. Overall, the magnitude of chemical weathering observed between the two stream systems is ultimately related to the nature of the underlying drift (cold and wet-based drift deposition), dispersal patterns of eolian fines, and variable stream discharge rates. Thus, incorporation of local fine-grained sediment derived from the underlying glacial drift deposits and distributed via the varying wind regimes within the hyper-arid climate into active stream channels may facilitate incongruent mineral dissolution and development of weathering products, and ultimately influence the composition and concentration of meltwater stream solutes.

1. Introduction

Weathering in polar climates is considered to be dominated by physical processes, including rock fragmentation due to thermal processes, and wind abrasion that produces ventifacts (Hall et al., 2002; Huh, 2003; Sepala, 2004; Putkonen et al., 2014). Chemical weathering in cold regions has been previously assumed as minimal owing to limited availability of liquid water, and low temperatures that slow reaction rates (Velbel, 1993; Lasaga et al., 1994; White and Blum, 1995; Anderson et al., 1997; Anderson, 2007; Hall et al., 2002; Goudie and Viles, 2012). However, in wet-based glacial regimes, mechanical

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grinding of sediments by glacial erosion can produce large volumes of unsorted sediment including fresh rock flour with high surface area susceptible to significant chemical weathering attributable to formation of chemically reactive sites on mineral grains (Anbeek, 1992, 1993; Anderson, 2005, 2007; Goudie and Viles, 2012). Chemical erosion rates in glacial systems are typically correlated with water discharge rates, and cation fluxes in these systems commonly reflect ready dissolution of soluble carbonate phases and leaching from abraded silicate minerals such as biotite (Anderson et al., 1997; Nezat et al., 2001). However, a recent long-term meltwater chemistry study within the temperate proglacial system of Austre Broggerbreen (Norway) (Nowak and Hodson, 2014) revealed enhanced silicate mineral weathering owing to exposure of fine-grained, chemically reactive sediments during glacial retreat associated with a transition from wet-based to cold-based conditions and decreased discharge. These results suggest that exposed mineral surface area may be even more important than water flux in controlling ion yields in wet-based glacial systems.

In the McMurdo Dry Valleys of Antarctica, cold-based glaciers currently dominate across the landscape. These valleys were subject to wet-based glaciation during the Oligocene, followed by development of cold-based glaciation during the Miocene (~13.6 Ma). The MDV have maintained cold, hyper-arid conditions since this time (Marchant et al., 1993; Denton and Sugden, 2005; Sugden et al., 2006; Bockheim, 2013). Cold-based glaciers are defined as those frozen to the rock substrate, suggesting minimal erosive impact on subjacent bedrock and sediment. However, some active basal sliding has been documented in the MDV, resulting in geomorphic features such as boulder-top abrasion, grooves, and thin drift deposits (Chinn, 1994; Cuffey et al., 2000; Atkins et al., 2002; Atkins, 2014). The various drift deposits that currently fill the MDV, however, reflect complex and differing glacial histories, and include derivation from both wet-based and/or cold-based glaciation.

Previous work on the magnitude and nature of chemical weathering in Antarctic streams has focused on assessing variations in solute concentrations within stream waters sourced from cold-based glaciers and their transport into ice-covered lakes (Green et al., 1988, 2005; Lyons et al., 1998, 2002, 2003; Nezat et al., 2001; Gooseff et al., 2002, 2004; Fortner et al., 2005, 2013; Welch et al., 2010; Stumpf et al., 2012). These solutes are attributed to dissolution of salts and carbonates and weathering of silicate minerals within channel and hyporheic soil sediments (Lyons et al., 1998; Gooseff et al., 2002; Stumpf et al., 2012). Based on observed solute trends, chemical weathering in MDV streams can occur at rates per unit area equivalent to wet-based glacial systems, despite prevailing low temperatures, seasonally restricted moisture availability, and minimal organic content (Nezat et al., 2001; Lyons et al., 2002; Gooseff et al., 2002; Welch et al., 2010; Stumpf et al., 2012). However, due to the complex history of the glacially derived till, these rates may reflect a relict of a former wet-based setting.

Despite well-documented observations of heightened solute loads in ephemeral Antarctic glacial streams, few studies directly assess the impact of silicate weathering on sediments within the stream hyporheic zone and/or identify potential weathering products (i.e., clays) (Lyons et al., 1998; Gooseff et al., 2002; Maurice et al., 2002). Here, we present geochemical data on fine-grained (<63 μm) hyporheic zone sediments from stream channels in both Wright and Taylor Valleys (Antarctica) to investigate the characteristics and potential variability of chemical weathering in ephemeral proglacial stream sediments within a modern cold-based glacial environment. In addition, we explore potential links among past glacial conditions (i.e., wet versus cold-based glaciation), eolian contributions, stream discharge, and supraglacial processes.

2. Geologic setting

The MDVs are a series of east-west trending, nearly ice-free valleys situated between the Transantarctic Mountains and the Ross Sea of Antarctica. The MDV region is classified as a hyper-arid, polar desert where mean annual temperatures range between −14.8 °C and −30.0 °C, and precipitation, typically in the form of snowfall, is <10 cm/yr (Clow et al., 1988; Fountain et al., 1999; Doran et al., 2002, 2008). The hydrologic elements of the MDV consist of glaciers, ephemeral streams, lakes, and shallow groundwater. Continuous permafrost occurs at shallow depths throughout the MDV, spatially restricting subsurface flow (Gooseff et al., 2011). Active stream flow is limited to the austral summer (approximately 6–12 weeks), when solar insolation warms the surfaces of valley glaciers and generates meltwater runoff, which flows off the glaciers and across valley drift to closed-basin lakes. Streamflow rates exhibit diel variation, and can fluctuate 5–10 fold within a single summer day (McKnight et al., 1999; Gooseff et al., 2011; McKnight, 2014). Meltwater exchange with drift sediments primarily occurs within the hyporheic zone of reactivated stream channels, defined as the saturated area underlying and adjacent to the streambed where water can flow before encountering permafrost (McKnight et al., 1999; Gooseff et al., 2002, 2013).

Additional shallow groundwater features include melt from localized snow patches, water tracks, and margins of streams and lakes, which, in conjunction with the hyporheic zone, mobilize solutes and provide suitable conditions for biotic growth and biogeochemical cycling (Barrett et al., 2009; Levy et al., 2011; Gooseff et al., 2013; Langford et al., 2014; Mikucki et al., 2015). Biotas in the MDV are generally restricted to cyanobacteria, algae, and mosses. Perennial algae typically grow within streams as mats that can endure long periods of desiccation and are common within Taylor Valley streams (McKnight et al., 1999, 2007).

Eolian processes in the MDV are critical to distributing nutrients, organic matter, and sediment onto glacier surfaces and into the hyporheic zones of the ephemeral stream channels, where these particulates may become entrained in meltwater runoff and into stream flow (Fortner et al., 2011; Sabacka et al., 2012; Deuerling et al., 2014). Winds blow upvalley from McMurdo Sound during the summer months, whereas strong down-valley winds sourced from the polar plateau prevail during the winter and can reach speeds up to 40 m/s (Doran et al., 2008). Summer foehn wind events can also result in adiabatic warming of the MDV region, leading to heightened temperatures and increased meltwater generation (Steinhoff et al., 2014). Wind-blown aerosols are typically either marine or locally sourced terrestrial material, and particulate concentrations are commonly higher on the western sides of glaciers due to the prevailing wind direction (Lyons et al., 2003; Bertler et al., 2004; Ayling and McGowan, 2006; Witherow et al., 2006; Williamson et al., 2007; Sabacka et al., 2012; Fortner et al., 2013; Deuerling et al., 2014).

This study focuses specifically on sample sites in eastern Wright (Clark Glacier stream) and eastern Taylor (Delta Stream and Goldman Glacier channel) Valleys (Fig. 1). Whereas granitic plutonic and metamorphic rocks underlie both field areas, the overlying drift deposits reflect differing glacial histories and contain materials of differing composition, texture, and age. In lower Wright Valley, drift deposits are underlain by the Brownworth (granite and quartz monzonite) and Denton (foliated granodiorite) plutons near the eastern end of the valley and adjacent to Wright Lower Glacier. Drift types in this region date to at least the Miocene and were largely emplaced prior to the Last Glacial Maximum (LGM). These drift deposits generally consist of a coarse-grained, heterogeneous mix of igneous and metamorphic clasts and were sourced from multiple cold-based glacial ice advances and retreats from the adjacent Wilson Piedmont Glacier and Ross Sea Embayment (Hall and Denton, 2005). The stream emanating from Clark Glacier (henceforth referred to as Clark Glacier stream) in Wright Valley crosses Brownworth drift, which is underlain by Trilogy drift near the glacier terminus and Loke drift near Lake Brownworth (Fig. 1). Brownworth drift is dominated by sand-size material and consists of two facies: 1) coarse sand diamicton, and 2) horizontally stratified sandy glaciolacustrine facies. The drift exhibits limited soil development and consists of a variety of basement clast types, including Ferrar