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Basalt weathering in an Arctic Mars-analog site

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ABSTRACT

The martian surface has undergone chemical and physical weathering in the past, and these processes may continue intermittently today. To explore whether martian rocks are likely to retain features indicative of weathering, we investigated how basaltic material weathers on Earth. Specifically, we investigated weathering of a Quaternary-aged basaltic flow at the Sverrefjell volcano in Svalbard, above the Arctic Circle. This flow weathered since deglaciation under cold, dry (<400 mm/yr) conditions. We analyzed a ~75-cm core of regolith for chemical loss and then characterized the mineralogical and morphological properties using electron microscopy (EM), X-ray diffraction (XRD), infrared (IR) spectroscopy and selective chemical dissolution. In addition, we ran colloidal dispersion, wetting/drying, and freeze/thaw experiments. In the regolith, we observed concentrations of short-range ordered (SRO) phases similar to those observed in warmer, wetter volcanic ash soils. IR and EM analyses of the clay-sized fraction were consistent with allophane as the predominant secondary phase. Selective chemical extractions targeting SRO phases indicated lower Al/Si ratios than those observed in volcanic soils reported in warmer localities, which we attribute to Si-rich allophane and/or abundant Si-rich rock coatings. The oxic circumneutral-pH colloidal dispersion experiments mobilized Al, Fe and Ti primarily as 260–415 nm particles and Ca, Mg and Na as solutes. Si was lost both in the colloidal and dissolved forms. Dispersed colloids likely contain allophane and ferrihydrite. Under anoxic conditions, dissolution of Fe oxide cements also released fines. The experiments help to explain elemental loss from the clay-sized regolith fraction at Svalbard: observed depletions in Ca, K, Mg and Na were likely due to solute loss, while particle-reactive Al, Fe, Si and Ti were mostly retained. Wetting/drying was observed to be as effective as freeze/thaw in driving material loss. It is thus possible that cyclic adsorption of water onto basaltic rocks in this dry climate may result in high physical spalling rates that in turn promote chemical leaching. Many observations at Sverrefjell are similar to inferences from Mars: the presence of SRO phases, Si-rich coatings, and/or Si-rich allophane, as well as the persistence of olivine. Given these similarities, it is inferred that Sverrefjell volcano is a good analog for martian weathering and that other processes operating at Sverrefjell may also have occurred on Mars, including Na leaching, surface spalling, and precipitation of Si-rich layers. Such processes could have occurred on Mars wherever basalts were exposed to water at circumneutral pH for thousands to tens of thousands of years.

1. Introduction

Although the average surface temperature on Mars is −60 °C (McKay et al., 1991), temperatures also rise above 0 °C (Jakosky et al., 2003), and a growing body of evidence suggests that liquid water has been present on the surface of the planet (Ehlmann et al., 2011a and references within). Consistent with chemical weathering resulting from the presence of water, martian rocks display what have been inferred to be weathering rinds (e.g., Thomas et al., 2005; Hausrath et al., 2008a). Thermal emission spectrometer and Compact Reconnaissance Imaging Spectrometer of Mars (CRISM) data further indicate the presence of both primary and secondary minerals, including plagioclase, pyroxene, olivine, phyllosilicates, zeolites, volcanic glasses, opaline silica and allophane (McSween et al., 2004; Morris et al., 2004; Michalski et al., 2006; Ehlmann et al., 2009; Ehlmann et al., 2011b; Rampe et al., 2012). A particularly important question with respect to weathering of basalts on Mars is the origin and age of short-range ordered (SRO) phases (Banin, 1996; Rampe et al., 2012; Bish et al., 2013).

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Although widespread acidic conditions have been hypothesized to have occurred across the surface of Mars (Hurowitz and McLennan, 2007), regions that have experienced near-neutral pH weathering are also thought to exist. For example, such weathering has been hypothesized in low-albedo regions (Ehlmann et al., 2008; Rampe et al., 2012). Recent results from the Curiosity rover further suggest alteration under near-neutral conditions (Grotzinger et al., 2014).

One way to determine whether martian rocks retain features indicative of water–rock reactions (chemical weathering) is to investigate how basaltic material weathers on Earth, especially in colder climates. Weathering of volcanic soils has been investigated at sites from around the world, including the cold climates of Alaska (Ping et al., 1988, 1989) and Iceland (Arnalds et al., 1995). Based on studies of weathering rinds, Colman (1982) observed the following order of mineral susceptibility during basalt dissolution: glass > olivine > pyroxene > plagioclase > K-feldspar. During such terrestrial basalt weathering, a variety of secondary phases also commonly form, including allophane (Colman, 1982; Stefansson and Gislason, 2001; Chadwick et al., 2003; Pokrovsky et al., 2005; Shikazono et al., 2005), halloysite (Shoji and Saigusa, 1977; Chadwick et al., 2003; Ziegler et al., 2013; Shikazono et al., 2005), Al-organic compounds (Ping et al., 1988; Pokrovsky et al., 2005) and smectite (Nesbitt and Wilson, 1992; Stefansson and Gislason, 2001; Pokrovsky et al., 2005; Rasmussen et al., 2010).

Many of the characteristics of the environment of the Sverrefjell volcano in Svalbard suggest it is a good Mars analog for weathering processes that are taking place or took place under circumneutral pH conditions on Mars: specifically, the basaltic composition, the dry climate, and the cold temperatures. Rocks at both Sverrefjell and Mars are basaltic in composition with volcanic and pyroclastic textures (Ming et al., 2006; Arvidson et al., 2008). Although basalts on Sverrefjell volcano are alkaline in composition (Skjelkvale et al., 1989) while those on Mars are tholeiitic (McSween et al., 2009), the two sites contain a similar assemblage of minerals including forsteritic olivine, augite, plagioclase, magnetite and volcanic glass (Skjelkvale et al., 1989; McSween et al., 2004; Morris et al., 2004; Michalski et al., 2006). Previous work has suggested that olivine and volcanic glass, present at both locations, dominate the initial weathering of basalts due to their greater solubilities (Hurowitz and McLennan, 2007; Hausrath et al., 2008b).

In addition to mineralogy, both Sverrefjell and the surface of Mars have experienced relatively limited exposure to water over time. For example, the persistence of olivine in the martian regolith (Michalski et al., 2005; Bish et al., 2013) is consistent with short contact time between martian rocks and aqueous solutions. Previous modeling results likewise suggest limited contact of martian rocks with water (Stopar et al., 2006; Olsen and Rimstidt, 2007; Hausrath et al., 2008a; Pike et al., 2011). In the case of Sverrefjell, weathering was previously assumed to be restricted to the 10,000-year period of time since the Last Glacial Maximum (Hausrath et al., 2008b). However, ice-free conditions may have extended back as long as 80 ky (Landvik et al., 2003). The average annual precipitation is <400 mm (Hanssen-Bauer and Forland, 1998; Hausrath et al., 2008b). Finally, the average annual temperature at Sverrefjell is -5 °C, with a range from -23 °C to 6 °C (Hanssen-Bauer and Forland, 1998). These values fall in the upper range of temperatures recorded by the Viking missions of 17 °C to -143 °C (Kieffer et al., 1977; Stopar et al., 2006) and encompass ranges expected in equatorial regions of Mars.

Previous work has also pointed to the region of Spitsbergen (where Sverrefjell is located) as a Mars analog site (Treiman et al., 2002). In this contribution, we investigate Sverrefjell volcano as a Mars analog that may provide insight into the mechanisms of chemical weathering of basalt in circumneutral pH fluids. In particular, we are interested in the relative abundance and identity of secondary phases that are forming as a result of weathering and the extent of loss of different elements. Because some volcanic soils are particularly rich in sub-micron sized particles (Dahlgren et al., 1993), we use short-term batch experiments to understand the colloidal size fractions in which different elements occur under oxic and anoxic conditions. To further investigate fine-particle production and related elemental loss mechanisms, wetting, freezing and drying experiments were completed on pristine Sverrefjell parent rock in the laboratory.

2. Materials and methods

2.1. Site background

Sverrefjell volcano is one of three Quaternary eruptive centers in northwestern Spitsbergen on the arctic archipelago of Svalbard. Based upon Ar–Ar age data, Treiman (2012) derived an eruption age of 1.05 ± 0.5 Ma. The volcano extends from a 3 km cross-sectional diameter base at sea level to an elevation of 500 m at the summit (Skjelkvale et al., 1989). It is composed of sequences of primitive alkali basaltic flows and pyroclastics with abundant xenoliths (Skjelkvale et al., 1989). The basalts contain phenocrysts of olivine and augite in a fine-grained groundmass of olivine, augite, plagioclase laths and titanomagnetite along with varying amounts of basaltic glass (Skjelkvale et al., 1989; Hanssen-Bauer and Forland, 1998). The nearest meteorological station to Sverrefjell is located in Ny Alesund (average annual temperature (T) = -6.4 °C, annual precipitation = 385 mm) (http://www.ssb.no/). The next closest station is Longyearbyen (annual average $T = -6.3$ °C, annual precipitation = 180.7 mm) (Hanssen-Bauer and Forland, 1998). Thus at Svalbard, $T \sim -5$ °C and precipitation is likely <400 mm.

The archipelago was inferred to have been most recently deglaciated ~10,000 years ago (Hausrath et al., 2008b); however, ice-free conditions may have occurred as early as 80,000 years ago (Landvik et al., 2003). Hald et al. (2007) used planktonic foraminifera in sediment cores to infer that sea surface temperatures were ~5 °C warmer than current temperatures between 10,000 and 9000 years BP and that temperatures remained relatively constant from 9000 years BP until the present. Today, the land surface at Sverrefjell volcano is characterized by rocky basalt covered occasionally by lichens and very limited plant cover.

2.2. Sampling methods

During the summer of 2004, a 74-cm loose regolith core made up of volcanic cinders was collected from the south side of the volcano at an elevation of ~300 m (Site 1 in Fig. 1). Around the regolith core, the land surface was characterized by cinders that looked similar to those in the core, with little to no true soil formation or obvious soil horizons. Using a hand auger, seven samples (Table 1) were collected as a function of depth until auger refusal, presumably marking the contact between the weathered volcanic cinders and the underlying basalt flow. The upper ~3 cm of a fractured rock sample from Site A (Fig. 1) was also analyzed by scanning electron microscopy. All samples were stored frozen in sterile Whirl-Pak® bags until analysis. A large and relatively pristine rock was selected from a basaltic dike at the Sverrefjell volcano for wetting/drying experiments.

2.3. Regolith chemical characterization

To investigate chemical losses during weathering, we measured elemental concentrations on three subsamples of air-dried regolith. For bulk chemical analysis, one set ("unsieved") was measured